Method And Apparatus For Dark Field Interferometric Confocal Microscopy

This claims the benefit of U.S. Provisional Application No. 60/448,250, filed February 19, 2003 and U.S. Provisional Application No. 60/448,360, filed February 19, 2003.

Technical Field

This invention relates to interferometric confocal microscopy.

Background of the Invention

There are number of different forms of differential confocal microscopy. In one differential form, the Nomarski microscope measures one component of a conjugated quadratures of fields corresponding to the electrical interference signal of two images superimposed in an image plane. In another differential form, the conjugated quadratures of a dark field are measured one point at a time. In another differential form, the conjugated quadratures of each of two fields corresponding to two images superimposed in an image plane are measured one point at a time. In commonly owned U.S. Provisional Patent Application No. 60/447,254 (ZI-40) entitled "Transverse Differential Interferometric Confocal Microscopy" and U.S. Patent Application No. _______ filed Feb. 13, 2004 (ZI-40) also entitled "Transverse Differential Interferometric Confocal Microscopy" both of which are by Henry A. Hill, it is taught how to practice transverse differential interferometric confocal microscopy. In commonly owned U.S. Provisional Patent Application No. 60/448,360 (ZI-41) entitled "Longitudinal Differential Interferometric Confocal Microscopy" and U.S. Patent Application No. _______ filed Feb. 19, 2004 (ZI-41) also entitled Longitudinal Differential Interferometric Confocal Microscopy" both of which are by Henry A. Hill, it is taught how to practice longitudinal differential interferometric confocal microscopy. The contents of both the cited U.S.

Provisional Applications and the cited U.S. Patent Applications are herein incorporated in their entirety by reference.

However, neither the prior art nor the two cited U.S. provisional patent applications or the two cited U.S. Patent Applications teach how to practice differential interferometric confocal microscopy wherein an array of conjugated quadratures of fields are measured jointly, where the components of each conjugated quadratures may be measured jointly, and where each conjugated quadratures represent a difference of conjugated quadratures of fields of converging beams subsequently scattered/reflected or transmitted by a common location on a substrate surface wherein one of the converging beams subsequently scattered/reflected from the location is focused to an image plane located above the substrate surface and the second of the converging beams subsequently scattered/reflected from the location is focused to an image plane located below the substrate surface.

Also, prior art does not teach how to practice dark field differential interferometric confocal microscopy wherein an array of conjugated quadratures of fields are measured jointly, where the components of each conjugated quadratures may be measured jointly, where each conjugated quadratures represents a difference of conjugated quadratures of fields of converging beams subsequently scattered/reflected from a common location on a substrate surface wherein one of the converging beams subsequently scattered/reflected or transmitted by the location is focused to an image plane located above the substrate surface and the second of the converging beams subsequently scattered/reflected or transmitted by the location is focused to an image plane located below the substrate surface, and where the nominal values of the conjugated quadratures of the array of conjugated quadratures is zero, *i.e.*, the field that is being measured is nominally dark.

Summary of the Invention

Embodiments of the present invention comprise interferometric confocal microscopy systems wherein an array of conjugated quadratures of fields are measured jointly, where the components of each conjugated quadratures may be

measured jointly, where each conjugated quadratures represents a difference of conjugated quadratures of fields of converging beams subsequently scattered/reflected or transmitted by a common location on a substrate surface wherein one of the converging beams subsequently scattered/reflected from the location is focused to an image plane located above the substrate surface and the second of the converging beams subsequently scattered/reflected or transmitted by the location is focused to an image plane located below the substrate surface, and where the nominal values of the conjugated quadratures of the array of conjugated quadratures may be adjusted as a set to be zero by controlling a single system parameter. The embodiments further comprise embodiments configured for operation in a dark field mode.

The embodiments of the present invention configured for operation in a dark field mode can be used to measure properties of a thin film on the surface of a substrate with a lateral spatial resolution approximately the same as the lateral spatial resolution of an associated interferometric confocal imaging system.

The reflection/scattering properties of a substrate may also be measured for different reflection/scattering or transmission polarization states of a measurement beam in embodiments of the present invention.

In general, in one aspect, the invention features a differential interferometric confocal microscope for measuring an object. The microscope includes: a source-side pinhole array; a detector-side pinhole array; and an interferometer that images the array of pinholes of the source-side pinhole array onto a first array of spots located in front of an object plane located near where the object is positioned and onto a second array of spots behind the object plane, wherein the first and second arrays of spots are displaced relative to each other in a direction that is normal to the object plane, said interferometer also (1) imaging the first arrays of spots onto a first image plane that is behind the detector-side pinhole array, (2) imaging the first array of spots onto a second image plane, (3) imaging the second array of spots onto the second image plane, and (4) imaging the second array of spots onto a third image plane that is in front of the plane defined by the detector-side pinhole array, wherein each spot of the imaged first array of

spots in the first image plane is aligned with a corresponding different spot of the imaged second array of spots in the second image plane and a corresponding different pinhole of the detector-side pinhole array, and wherein each spot of the imaged first array of spots in the second image plane coincides with a corresponding different spot of the imaged second array of spots in the second image plane and is aligned with a corresponding different pinhole of the detector-side pinhole array.

In general, in another aspect, the invention features a differential interferometric confocal microscope for measuring an object and which includes: a source-side pinhole array for producing an array of input beams; and a detector-side pinhole array; and an interferometer including: a first optical element providing a first reflecting surface; a second optical element providing a second reflecting surface; and a beam splitter positioned between the first and second optical elements, wherein the beam splitter produces from the array of input beams a first array of measurement beams and a second array of measurement beams, wherein the first reflecting surface participates in focusing the first array of measurement beams onto a first array of locations on a first object plane in object space and the second reflecting surface participates in focusing the second array of measurement beams onto a second array of locations on a second object plane in object space, said first and second object planes being parallel to and displaced from each other, wherein the first array of measurement beams generates a first array of return beams from the object and the second array of measurement beams generates a second array of return beams from the object, wherein the first and second reflecting elements participate in producing from the first array of return beams (1) a first array of converging beams that converge to a first array of spots on a first image plane and (2) a second array of converging beams that converge onto a second array of spots on a second image plane, wherein the first and second reflecting elements participate in producing from the second array of return beams (1) a third array of converging beams that converge onto the second array of spots on the second image plane and (2) a fourth array of converging beams that converge onto a third array of spots on a third image plane, wherein said first and third image planes are adjacent to and on opposite sides of the detector-side pinhole array, and the second image plane lies between the first and third

image planes, and wherein the detector-side pinhole array combines the first, second, third, and fourth arrays of converging beams to form an array of output beams.

Other embodiments include one ore more of the following features. A single pinhole array serves as both the source-side pinhole array and the detector-side pinhole array. The first optical element is located between said single pinhole array and the beam splitter and wherein the second optical element is located between a location at which the object is positioned during use and the beam splitter, wherein the first reflecting surface has a center of curvature for which there is a corresponding conjugate as viewed through the beam splitter, and wherein the second reflecting surface has a center of curvature that is displaced relative to the corresponding conjugate of the center of curvature of the first reflecting surface. The conjugate of the center of curvature of the first reflecting surface and the center of curvature of the second reflecting surface are displaced from each other in a direction that is normal to a plane defined by the beam splitter. The first reflecting surface participates in focusing the first array of measurement beams via the beam splitter onto the first array of locations and the second reflecting surface participates in focusing the second array of measurement beams via the beam splitter onto the second array of locations. The first reflecting surface is substantially concentric with a point on the object. The second optical element provides a refracting surface positioned between the object and the beam splitter to receive light rays from the object. The first reflecting surface substantially conforms to a sphere having a first radius and the refracting surface conforms to a sphere having a second radius, wherein the first radius is greater than the second radius. The first optical element provides a refracting surface positioned between the beam splitter and said single pinhole array. The second reflecting surface is substantially concentric with an image point on said single pinhole array. The second reflecting surface substantially conforms to a sphere having a first radius and the refracting surface conforms to a sphere having a second radius, wherein the first radius is greater than the second radius. The said single pinhole array is a two-dimensional array. The two-dimensional array is of equally-spaced holes. The equally-spaced holes are circular apertures.

An advantage of at least one embodiment of the present invention is that the fields of beams scattered/reflected or transmitted by a pair of locations on a substrate surface are generated by a single confocal pinhole.

Another advantage of at least one embodiment of the present invention is that reference beam components of an array of reference beams used in generation of electrical interference signals corresponding to measured conjugated quadratures of fields of a pair of converging beams scattered/reflected or transmitted by a common spot on a substrate are identical.

Another advantage of at least one embodiment of the present invention is that components of background beams generated by measurement beam components subsequently scattered/reflected or transmitted at a common spot on a substrate surface are substantially identical at a confocal pinhole.

Another advantage of at least one embodiment of the present invention is that the spatial filtering of fields of a pair of converging beams scattered/reflected or transmitted at a common spot on a substrate surface is performed by a single confocal pinhole.

Another advantage of at least one embodiment of the present invention is that information about a substrate surface is obtained with an interferometric confocal imaging system operating in a dark field mode.

Another advantage of at least one embodiment of the present invention is that information about a substrate surface is obtained with reduced systematic and statistical errors.

Another advantage of at least one embodiment of the present invention is the generation of a significant increase in throughput because the intensity of an input beam may be significantly increased without saturation of a detector system.

Another advantage of at least one embodiment of the present invention is that an array of conjugated quadratures of the fields of arrays of pairs of converging beams scattered/reflected or transmitted by an array of common spots on a substrate surface is measured jointly and the components of each conjugated quadratures may be measured jointly.

Another advantage of at least one embodiment of the present invention is that an array of conjugated quadratures of the fields of arrays of pairs of converging beams scattered/reflected or transmitted by an array of common spots on a substrate surface may be measured using different reflection/scattering or transmission polarization states of a measurement beam.

Another advantage of at least one embodiment of the present invention is that information is obtained about critical dimensions and locations of sub-wavelength artifacts on a substrate surface.

Another advantage of at least one embodiment of the present invention is that information is obtained about the sizes and locations of sub-wavelength defects on a substrate surface.

Another advantage of at least one embodiment of the present invention is that information may be obtained about one-dimensional and two-dimensional profiles of a substrate surface.

Another advantage of at least one embodiment of the present invention is that imaging of a substrate surface profile with a lateral resolution of the order of 100 nm and a longitudinal resolution of the order of 200 nm may be obtained with a working distance of the order of a mm.

Brief Description of the Drawings

Fig. **1a** is a diagram of an interferometric system used to make differential measurements of conjugated quadratures of fields of beams scattered/reflected or transmitted by a substrate.

Fig. **1b** is a schematic diagram of a beam-conditioner configured to operate in a two-frequency generator and phase-shifter.

Fig. **1c** is a schematic diagram of a beam-conditioner configured to operate in a two-frequency generator and frequency-shifter.

Fig. **2a** is a schematic diagram of a confocal microscope system.

Fig. **2b** is a schematic diagram of catadioptric imaging system.

Fig. **2c** is a schematic diagram of beams focused to spots at a pinhole array used in a confocal microscope system.

Fig. **2d** is a schematic diagram of beams focused to spots in a catadioptric imaging system.

Fig. **2e** is a schematic diagram of beams focused to spots in a catadioptric imaging system.

Fig. **3** is a schematic diagram of an interferometric confocal imaging system used to make differential measurements of conjugated quadratures of fields of beams scattered/reflected by a substrate.

Detailed Description

An array of conjugated quadratures of fields is measured interferometrically by a confocal interferometer and detector system wherein each conjugated quadratures corresponds to a difference of conjugated quadratures of fields of a pair of converging beams scattered/reflected or transmitted by a common spot on/in a substrate. The array of conjugated quadratures measured jointly, *i.e.*, simultaneously. In addition, the components of each conjugated quadratures may be measured jointly. The converging beams subsequently converge as focused beams to spots located above and below the common spot. The relative phases of the pair of converging beams may be adjusted so that the differences of the complex amplitudes of the fields of the pair of converging beams scattered/reflected or transmitted by the common spot are nominally zero, *i.e.*, information may be obtained about the substrate with the interferometer and detector system operating in a dark field mode and using if required different reflection/scattering polarization states of a measurement beam. Operation in a dark field mode leads to both reduced systematic and statistical errors in the information. The information may comprise the profile of one or more surfaces of a substrate and the thickness profile of a thin film layer on/in a substrate as well as information about critical dimensions of features on a substrate and the size and location of sub-wavelength defects.

In one embodiment, an image plane of an interferometric confocal imaging system comprises a superposition of two images of a substrate surface wherein each of the two superimposed images corresponds to a partially defocused image of a common location on the substrate surface. The two partially defocused images correspond to conjugate spots that are displaced longitudinally relative to each other at the substrate surface. An array of conjugated quadratures of fields representing the superimposed images are measured jointly and the components of each conjugated quadratures may be measured jointly. The longitudinal separation of the image planes of the beams generating the partially defocused images of the substrate surface is of the order of the longitudinal resolution of the interferometric confocal imaging system. The respective conjugated quadrature of the a is $a\sin\phi$ when the quadrature $x(\phi)$ of the field is $a\cos\phi$.

In another embodiment, the relative phases of two converging beams subsequently scattered/reflected or transmitted at a common location on a substrate surface may be adjusted by confocal imaging system parameters so that conjugated quadratures of an array of conjugated quadratures of fields of the converging beams scattered/reflected or transmitted by the common location are nominally zero, *i.e.*, information is obtained about the substrate surface with the interferometric imaging system operating in a dark field mode. Different reflection/scattering or transmission polarization states of a measurement beam may also be used.

A general description of embodiments incorporating various aspects of the present invention will first be given wherein the embodiments comprise an interferometer system that uses either a single-, double, bi-, or quad-homodyne detection and a first array of partially defocused images of an array of a set of locations on a substrate surface and a second array of partially defocused images of an array of the same set of locations on the substrate surface are superimposed on an image plane of the interferometer system. The longitudinal separation of the image planes of the beams generating the partially defocused images of the substrate surface is of the order of the longitudinal resolution of the interferometer system.

There is a one-to-one mapping of a location in the superimposed image space to a common location on the surface of the substrate.

Referring to Fig. **1a**, an interferometer system is shown diagrammatically comprising an interferometer generally shown as numeral **10**, a source **18**, beam-conditioner **22**, detector **70**, an electronic processor and controller **80**, and a measurement object or substrate **60**. Source **18** and beam conditioner **22** generate input beam **24** comprising one or more frequency components. Source **18** is a pulsed source. Two or more of the frequency components of input beam **24** may be coextensive in space and may have the same temporal window function.

Reference and measurement beams are generated in interferometer **10** for each of the frequency components of beam **24**. The measurement beam generated in interferometer **10** is one component of beam **28** and imaged to form an array of pairs of partially defocused images on the surface of substrate **60**. Beam **28** further comprises a return reflected/scattered measurement beam that is generated by the reflection/scattering or transmission of the measurement beam component of beam **28** at the array of pairs of partially defocused images on the surface of substrate **60**. Interferometer **10** superimposes the two arrays of components of the return measurement beam corresponding to the two arrays components of beam **28** reflected/scattered or transmitted at the arrays of the pairs of defocused images to form a single array of superimposed images of return measurement beam components of beam **28**. The return measurement beam components of beam **28** are subsequently combined with the reference beam in interferometer **10** to form output beam **32**.

Output beam **32** is detected by detector **70** to generate an electrical interference signal **72**. Detector **70** may comprise an analyzer to select common polarization states of the reference and return measurement beam components of beam **32** to form a mixed beam. Alternatively, interferometer **10** may comprise an analyzer to select common polarization states of the reference and return measurement beam components such that beam **32** is a mixed beam.

Two different modes are described for the acquisition of the electrical interference signals **72**. The first mode to be described is a step and stare mode wherein substrate **60** is stepped between fixed locations corresponding to locations where image information is desired. The second mode is a scanning mode. In the step and stare mode for generating a one-dimensional and a two-dimensional surface profile of substrate **60**, substrate **60** mounted in wafer chuck **84**/stage **90** is translated by stage **90**. The position of stage **90** is controlled by transducer **82** according to servo control signal **78** from electronic processor and controller **80**. The position of stage **90** is measured by metrology system **88** and position information acquired by metrology system **88** is transmitted to electronic processor and controller **80** to generate an error signal for use in the position control of stage **90**. Metrology system **88** may comprise for example linear displacement and angular displacement interferometers and cap gauges.

Electronic processor and controller **80** directs the translation of wafer stage **90** to a desired position and then acquires a set of four electrical interference signal values. After the acquisition of the sequence of four electrical interference signals, electronic processor and controller **80** then repeats the procedure for the next desired position of stage **90**. The elevation and angular orientation of substrate **60** is controlled by transducers **86A** and **86B**.

The second mode for the acquisition of the electrical interference signal values is next described wherein the electrical interference signal values are obtained with the position of stage **90** scanned in one or more directions. In the scanning mode, source **18** is pulsed at times controlled by signal **92** from signal processor and controller **80**. Source **18** is pulsed at times corresponding to the registration of the conjugate image of confocal pinholes or pixels of detector **70** with positions on and/or in substrate **60** for which image information is desired.

There will be a restriction on the duration or "pulse width" of a beam pulse τ_{p1} produced by source **18** as a result of the continuous scanning mode used in the third variant of the first embodiment. Pulse width τ_{p1} will be a parameter that in

part controls the limiting value for spatial resolution in the direction of a scan to a lower bound of

$$\tau_{p1}V\ , \tag{1}$$

where V is the scan speed. For example, with a value of $\tau_{p1} = 50\text{ nsec}$ and a scan speed of $V = 0.20$ m/sec, the limiting value of the spatial resolution $\tau_{p1}V$ in the direction of scan will be

$$\tau_{p1}V\ = 10\text{ nm}\ . \tag{2}$$

Pulse width τ_{p1} will also determine the minimum frequency difference that can be used in the bi- and quad-homodyne detection methods. In order that there be no contributions to the electrical interference signals from interference between fields of conjugated quadratures, the minimum frequency spacing $\Delta f_{\min}$ is expressed as

$$\Delta f_{\min} \gg \frac{1}{\tau_{p1}}\ . \tag{3}$$

For an example of $\tau_{p1} = 50\text{ nsec}$, $1/\tau_{p1} = 20\text{ MHz}$.

For certain embodiments, the frequencies of input beam **24** are controlled by signals **74** and/or **92** from signal processor and controller **80** to correspond to the frequencies that will yield the desired phase shifts between the reference and return measurement beam components of output beam **32**. Alternatively in certain other embodiments, the relative phases of reference and measurement beam components of input beam **24** are controlled by signal **74** and/or **92** from signal processor and controller **80** to correspond to the desired phase shifts between the reference and return measurement beam components of output beam **32**. In the first mode, *i.e.*, the

step and stare mode, each set of the sets of arrays of four electrical interference signal values corresponding to the set of four phase shift values are generated by a single pixel of detector **70** for single- and bi-homodyne detection method, by two pixels of detector **70** for the quad-homodyne detection method, and by four pixels of detector **70** for the double-homodyne detection methods. In the second mode for the acquisition of the electrical interference signal values, each corresponding set of four electrical interference signal values are generated by a conjugate set of four different pixels of detector **70** for each of the four homodyne detection methods. Thus in the first mode of acquisition, the differences in pixel efficiency are compensated in the signal processing by signal processor and controller **80** for the double-, bi-, and quad-homodyne detection methods and in the second mode of acquisition, the differences in pixel efficiency and the differences in sizes of pinholes in confocal pinhole arrays are compensated in the signal processing by signal processor and controller **80** as described in the subsequent description of the homodyne detection methods. The joint measurements of conjugated quadratures of fields generated by electric processor and controller **80** are subsequently described in the description of the bi- and quad homodyne detection methods.

In practice, known phase shifts are introduced between the reference and measurement beam components of output beam **32** by two different techniques. In one technique, phase shifts are introduced between the reference and measurement beam components for each of the at least two frequency components by source **18** and beam-conditioner **22** as controlled by signals **92** and **74**, respectively, from electronic processor and controller **80**. In the second technique, phase shifts are introduced between the reference and measurement beam components for each of the frequency components as a consequence of frequency shifts introduced to the frequency components of input beam **24** by source **18** and beam-conditioner **22** as controlled by signals **92** and **74**, respectively, from electronic processor and controller **80**.

There are different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments. Reference is made to

Fig. **1b** where beam-conditioner **22** is configured as a two-frequency generator and a phase-shifter and source **18** is configured to generate beam **20** with one frequency component. The two-frequency generator and phase-shifter configuration comprises acousto-optic modulators **1020, 1026, 1064**, and **1068**; polarizing beam-splitters **1030, 1042, 1044**, and **1056**; phase-shifters **1040** and **1052**; half wave phase retardation plates **1072** and **1074**; non-polarizing beam-splitter **1070**, and mirrors **1036, 1038, 1050, 1054**, and **1056**.

Input beam **20** is incident on acousto-optic modulator **1020** with a plane of polarization parallel to the plane of Fig. **1b**. A first portion of beam **20** is diffracted by acousto-optic modulator **1020** as beam **1022** and then by acousto-optic modulator **1026** as beam **1028** having a polarization parallel to the plane of Fig. **1b**. A second portion of beam **20** is transmitted as a non-diffracted beam **1024** having a plane of polarization parallel to the plane of Fig. **1b**. The acoustic power to acousto-optic modulator **1020** is adjusted such that beams **1022** and **1024** have nominally the same intensity.

Acousto-optic modulators **1020** and **1026** may be of either the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. The frequency shifts introduced by acousto-optic modulators **1020** and **1026** are of the same sign and equal to $1/4$ of the desired frequency shift between the two frequency components of input beam **24**. Also the direction of propagation of beam **1028** is parallel to the direction of propagation of beam **1024**.

Beam **1024** is diffracted by acousto-optic modulators **1064** and **1068** as beam **1082** having a polarization parallel to the plane of Fig. **1b**. Acousto-optic modulators **1064** and **1068** may be of either the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. The frequency shifts introduced by acousto-optic modulators **1064** and **1068** are of the same sign and equal to 1/4 of the desired frequency shift between the two frequency components of input beam **24**. Also the direction of propagation of beam **1082** is parallel to the direction of propagation of beam **1024**.

Beams **1028** and **1082** are incident on half-wave phase retardation plates **1072** and **1074**, respectively, and transmitted as beams **1076** and **1078**, respectively. Half-wave phase retardation plates **1072** and **1074** are oriented such that the planes of polarization of beams **1076** and **1078** are at 45 degrees to the plane of Fig. **1b**. The components of beams **1076** and **1078** polarized parallel to the plane of Fig. **1b** will be used as the measurement beam components in interferometer **10** and the components of beams **1076** and **1078** polarized orthogonal to the plane of Fig. **1b** will be used as the reference beam components in interferometer **10**.

Continuing with reference to Fig. **1b**, beam **1076** is incident on polarizing beam-splitter **1044** and the respective measurement and reference beam components transmitted and reflected, respectively, as beams **1046** and **1048**, respectively. Measurement beam component **1046** is transmitted by polarizing beam-splitter **1056** as a measurement beam component of beam **1058** after reflection by mirror **1054**. Reference beam component **1048** is reflected by polarizing beam-splitter **1056** as reference beam component of beam **1058** after reflection by mirror **1050** and transmission by phase-shifter **1052**. Beam **1058** is incident on beam-splitter **1070** and a portion thereof is reflected as a component of beam **24**.

Beam **1078** is incident on polarizing beam-splitter **1030** and the respective measurement and reference beam components transmitted and reflected, respectively, as beams **1032** and **1034**, respectively. Measurement beam component **1032** is transmitted by polarizing beam-splitter **1042** as a measurement beam component of beam **1060** after reflection by mirror **1036**. Reference beam component **1034** is reflected by polarizing beam splitter **1042** as reference beam component of beam **1060** after reflection by mirror **1038** and transmission by phase-shifter **1040**. Beam **1060** is incident on beam-splitter **1070** and a portion thereof is transmitted as a component of beam **24** after reflection by mirror **1056**.

Phase-shifters **1052** and **1040** introduce phase shifts between respective reference and measurement beams according to signal **74** from electronic processor and controller **80** (see Fig. **1a**). A schedule of the respective phase shifts is described in the subsequent discussions of homodyne detection methods. Phase-

shifters **1052** and **1040** may be for example of the optical-mechanical type comprising for example prisms and piezoelectric translators or of the electro-optical modulator type.

Beam **24** that exits the two-frequency generator and phase shift configuration of beam-conditioner **22** comprises one reference beam and measurement beam having one frequency, a second reference beam and measurement beam having a second frequency component, and relative phases of the reference beams and the measurement beams that are controlled by electronic processor and controller **80**.

Continuing with a description of different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments, reference is made to Fig. **1c** where beam-conditioner **22** is configured as a two-frequency generator and a frequency shifter. The two-frequency generator and frequency-shifter configuration comprises acousto-optic modulators **1120**, **1126**, **1130**, **1132**, **1142**, **1146**, **1150**, **1154**, **1058**, and **1062**; beam-splitter **1168**; and mirror **1166**.

Source **18** is configured to generate beam **20** with a single frequency component. Beam **20** is incident on acousto-optic modulator **1120** with a plane of polarization parallel to the plane of Fig. **1c**. A first portion of beam **20** is diffracted by acousto-optic modulator **1120** as beam **1122** and then by acousto-optic modulator **1126** as beam **1128** having a polarization parallel to the plane of Fig. **1c**. A second portion of beam **20** is transmitted as a non-diffracted beam **1124** having a plane of polarization parallel to the plane of Fig. **1c**. The acoustic power to acousto-optic modulator **1120** is adjusted such that beams **1122** and **1124** have nominally the same intensity.

Acousto-optic modulators **1120** and **1126** may be of either the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. The frequency shifts introduced by acousto-optic modulators **1120** and **1126** are of the same sign and equal to $1/2$ of a frequency shift Δf that will generate in interferometer **10** a relative $\pi/2$ phase shift between a corresponding reference beam and a measurement beam that have a relative change in frequency equal to the frequency

shift. The direction of propagation of beam **1128** is parallel to the direction of propagation of beam **1124**.

Continuing with Fig. **1c**, beam **1128** is incident on acousto-optic modulator **1132** and is either diffracted by acousto-optic modulator **1132** as beam **1134** or transmitted by acousto-optic modulator **1132** as beam **1136** according to control signal **74** (see Fig. **1a**) from electronic processor and controller **80**. When beam **1134** is generated, beam **1134** is diffracted by acousto-optic modulators **1142**, **1146**, and **1150** as a frequency-shifted beam component of beam **1152**. The frequency shifts introduced by acousto-optic modulators **1132**, **1142**, **1146**, and **1150** are all in the same direction and equal in magnitude to $\Delta f/2$. Thus the net frequency shift introduced by acousto-optic modulators **1132**, **1142**, **1146**, and **1150** is $\pm 2\Delta f$ and will generate a relative π phase between the respective reference and measurement beams in interferometer **10**. The net frequency shift introduced by acousto-optic modulators **1120**, **1126**, **1132**, **1142**, **1146**, and **1150** is $\Delta f \pm 2\Delta f$ and will generate a respective relative phase shift of $\pi/2 \pm \pi$ between the respective reference and measurement beams in interferometer **10**.

When beam **1136** is generated, beam **1136** is transmitted by acousto-optic modulator **1150** according to control signal **74** from electronic processor and controller **80** as a non-frequency shifted beam component of beam **1152** with respect to beam **1128**. The frequency shift introduced by acousto-optic modulators **1120**, **1126**, and **1150** is Δf and will generate a respective relative phase shift of $\pi/2$ between the respective reference and measurement beams in interferometer **10**.

Beam **1124** is incident on acousto-optic modulator **1130** and is either diffracted by acousto-optic modulator **1130** as beam **1140** or transmitted by acousto-optic modulator **1130** as beam **1138** according to control signal **74** from electronic processor and controller **80**. When beam **1140** is generated, beam **1140** is diffracted by acousto-optic modulators **1154**, **1158**, and **1162** as a frequency-shifted beam component of beam **1164**. The frequency shifts introduced by acousto-optic modulators **1130**, **1154**, **1158**, and **1162** are all in the same direction and equal to $\pm\Delta f/2$. Thus the net frequency shift introduced by acousto-optic modulators **1130**,

1154, **1158**, and **1162** is $\pm\Delta f/2$ and will generate a relative phase shift of π between the respective reference and measurement beams on transit through interferometer **10**. The net frequency shift introduced by acousto-optic modulators **1120**, **1130**, **1154**, **1158**, and **1162** is $\pm\Delta f/2$ and will generate a respective relative phase shift of $\pm\pi$ between the respective reference and measurement beams on transit through interferometer **10**

When beam **1138** is generated, beam **1138** is transmitted by acousto-optic modulator **1162** according to control signal **74** from electronic processor and controller **80** as a non-frequency shifted beam component of beam **1164**. The frequency shift introduced by acousto-optic modulators **1120**, **1130**, and **1162** is 0 and will generate a respective relative phase shift of 0 between the respective reference and measurement beams on transit through interferometer **10**.

Beams **1152** and **1164** may be used directly as input beam **24** when an embodiment requires spatially separated reference and measurement beams for an input beam. When an embodiment requires coextensive reference and measurement beams as an input beam, beam **1152** and **1164** are next combined by beam-splitter **1168** to form beam **24**. Acousto-optic modulators **1120**, **1126**, **1130**, **1132**, **1142**, **1146**, **1150**, **1154**, **1058**, and **1062** may be either of the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. Beams **1152** and **1164** are both polarized in the plane of Fig. **1c** for either non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type and beam-splitter **1168** is of the non-polarizing type.

With a continuation of the description of different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments, source **18** will preferably comprise a pulsed source. There are a number of different ways for producing a pulsed source [see Chapter 11 entitled "Lasers", *Handbook of Optics*, **1**, 1995 (McGraw-Hill, New York) by W. Silfvast]. Each pulse of source **18** may comprise a single pulse or a train of pulses such as generated by a mode locked Q-switched Nd:YAG laser. A single pulse train is

referenced herein as a pulse sequence and a pulse and a pulse sequence are used herein interchangeably.

Source **18** may be configured in certain embodiments to generate one or more frequencies by techniques such as described in a review article entitled "Tunable, Coherent Sources For High-Resolution VUV and XUV Spectroscopy" by B. P. Stoicheff, J. R.Banic, P. Herman, W. Jamroz, P. E. LaRocque, and R. H. Lipson in *Laser Techniques for Extreme Ultraviolet Spectroscopy*, T.J. McIlrath and R.R. Freeman, Eds., (American Institute of Physics) p 19 (1982) and references therein. The techniques include for example second and third harmonic generation and parametric generation such as described in the articles entitled "Generation of Ultraviolet and Vacuum Ultraviolet Radiation" by S. E. Harris, J. F. Young, A. H. Kung, D. M. Bloom, and G. C. Bjorklund in *Laser Spectroscopy I*, R. G. Brewer and A. Mooradi, Eds. (Plenum Press, New York) p 59, (1974) and "Generation of Tunable Picosecond VUV Radiation" by A. H. Kung, *Appl. Phys. Lett.* **25**, p 653 (1974). The contents of the three cited articles are herein incorporated in their entirety by reference.

The output beams from source **18** comprising two or four frequency components may be combined in beam-conditioner **22** by beam-splitters to form coextensive measurement and reference beams that are either spatially separated or coextensive as required in various embodiments. When source **18** is configured to furnish two or four frequency components, the frequency shifting of the various components required in certain embodiments may be introduced in source **18** for example by frequency modulation of input beams to parametric generators and the phase shifting of reference beams relative to measurement beams in beam-conditioner **22** may be achieved by phase shifters of the optical-mechanical type comprising for example prisms or mirrors and piezoelectric translators or of the electro-optical modulator type.

The general description of embodiments incorporating aspects of the present invention is continued with reference to Fig. **1a**. Input beam **24** is incident on interferometer **10** wherein reference beams and measurement beams are present in

input beam **24** or are generated from input beam **24** in interferometer **10**. The reference beams and measurement beams comprise two arrays of reference beams and two arrays of measurement beams wherein the arrays may comprise arrays of one element. The arrays of measurement beams are incident on or focused on and/or in substrate **60** and arrays of return measurement beams are generated by reflection/scattering and/or transmission by the substrate. In the case of single element arrays for the reference beams and measurement beams, the measurement beams are generally reflected or transmitted by substrate **60**. The arrays of reference beams and return measurement beams are combined by a beam-splitter to form two arrays of output beam components. The arrays of output beam components are mixed with respect to state of polarization either in interferometer **10** or in detector **70**. The arrays of output beams are subsequently focused to spots on pixels of a multi-pixel or single pixel detector as required and detected to generate electrical interference signal **72**.

There are four different implementations of the homodyne detection method that are used in interferometric embodiments. The four different implementations are referred to as single-, double-, bi-, and quad-homodyne detection methods. For the single-homodyne detection method, input beam **24** comprises a single frequency component and a set of four measurements of the array of electrical interference signals **72** is made. For each of the four measurements of the array of electrical interference signals **72**, a known phase shift is introduced between the reference beam component and respective return measurement beam components of output beam **32**. The subsequent data processing procedure used to extract the conjugated quadratures of the reflected and/or scattered or transmitted return measurement beam for an input beam comprising a single frequency component is described for example in commonly owned U.S. Patent No. 6,445,453 (ZI-14) entitled "Scanning Interferometric Near-Field Confocal Microscopy" by Henry A. Hill, the contents of which are herein incorporated in their entirety by reference.

The double-homodyne detection method uses input beam **24** comprising four frequency components and four detectors to obtain measurements of electrical

interference signals that are subsequently used to obtain conjugated quadratures. Each detector element of the four detector elements obtains a different one of the four electrical interference signal values with the four electrical interference signal values obtained simultaneously to compute the conjugated quadratures for a field. Each of the four electrical interference signal values contains only information relevant to one orthogonal component of the conjugated quadratures. The double-homodyne detection used herein is related to the detection methods such as described in Section IV of the article by G. M D'ariano and M G. A. Paris entitled "Lower Bounds On Phase Sensitivity In Ideal And Feasible Measurements," *Phys. Rev. A* 49, 3022-3036 (1994). Accordingly, the double-homodyne detection method does not make joint determinations of conjugated quadratures of fields wherein each electrical interference signal value contains information simultaneously about each of two orthogonal components of the conjugated quadratures.

The bi- and quad-homodyne detection methods obtain measurements of electrical interference signals wherein each measured value of an electrical interference signal contains simultaneously information about two orthogonal components of conjugated quadratures. The two orthogonal components correspond to orthogonal components of conjugated quadratures such as described in cited U.S Provisional Patent Application No. 60/442,858 (ZI-47) and cited U.S. Patent Application filed Jan. 27, 2004 (ZI-47) entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered and Transmitted Beams by an Object in Interferometry."

Conjugated quadratures of fields of the return measurement beam are obtained by single-, double-, bi-, and quad- homodyne detection methods in the interferometric embodiments. For each of the homodyne detection methods, a set of four measurements of the array of electrical interference signals **72** is made. For each of the four measurements of the array of electrical interference signals **72**, a known phase shift is introduced between the reference beam components and respective return measurement beam components of output beam **32**. A nonlimiting

example of a known set of phase shifts comprise 0, $\pi/4$, $\pi/2$, and $3\pi/2$ radians, mod 2π.

Input beam **24** comprises for interferometric embodiments one frequency component for the single-homodyne detection method. For the bi-homodyne detection method, input beam **24** comprises two frequency components and for double- and quad-homodyne detection methods, input beam **24** comprises four frequency components. The phase shifts are generated by either shifting the frequencies of frequency components of input beam **24** between known frequency values or by introducing phase shifts between the reference and measurement beam components of input beam **24**. In certain of the interferometric embodiments, there is a difference between the optical path lengths of the reference beam components and the respective return beam components of output beam components such for output beam **32** in interferometer **10**. As a consequence, a change in frequency of a frequency component of input beam **24** will generate a relative phase shift between the corresponding reference beam components and the respective return beam components of output beam **32**.

For an optical path difference L between the reference beam components and the respective return measurement beam components of output beam **32**, there will be for a frequency shift Δf a corresponding phase shift φ where

$$\varphi = 2\pi L\left(\frac{\Delta f}{c}\right) \tag{4}$$

and c is the free space speed of light. Note that L is not a physical path length difference and depends for example on the average index of refraction of the measurement beam and the return measurement beam paths. For an example of a phase shift $\varphi = \pi, 3\pi, 5\pi, \ldots$ and a value of $L = 0.25$ m, the corresponding frequency shifts are Δf = 600 MHz, 1.8 GHz, 3.0 GHz, … .

The frequencies of components of input beam **24** are determined by the mode of operation of source **18** and of beam-conditioner **22** according to control signals **92** and **74**, respectively, generated by electronic processor and controller **80**.

Referring to the bi-homodyne detection method, a set of four electrical interference signal values are obtained for each pair of spots in or on substrate **60** being imaged such as described in commonly owned U.S. Provisional Patent Application No. 60/442,858 (ZI-47) and entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered Beams by an Object in Interferometry" and U.S. Patent Application filed Jan. ___, 2004 (ZI-47) and entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered and Transmitted Beams by an Object in Interferometry" both of which are by Henry A. Hill. The contents of both the cited U.S. Provisional Patent Application and the U.S. Patent Application are herein incorporated in their entirety by reference. The set of four electrical interference signal values $S_j,\ j=1,2,3,4$ used for obtaining conjugated quadratures of fields for a single a spot on and/or in a substrate being imaged is represented for the bi-homodyne detection within a scale factor by the formula

$$S_j = P_j \begin{Bmatrix} \xi_j^2|A_1|^2 + \zeta_j^2|B_1|^2 + \eta_j^2|C_1|^2 + \zeta_j\eta_j 2|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_j} \\ +\xi_j\zeta_j 2|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_j} + \varepsilon_j\xi_j\eta_j 2|A_1||C_1|\cos\varphi_{A_1C_1} \\ +\xi_j^2|A_2|^2 + \zeta_j^2|B_2|^2 + \eta_j^2|C_2|^2 + \zeta_j\eta_j 2|B_2||C_2|\cos\varphi_{B_2C_2\gamma_j} \\ +\xi_j\zeta_j 2|A_2||B_2|\cos\varphi_{A_2B_2\gamma_j} + \gamma_j\xi_j\eta_j 2|A_2||C_2|\cos\varphi_{A_2C_2} \end{Bmatrix} \quad (5)$$

where coefficients A_1 and A_2 represent the amplitudes of the reference beams corresponding to the first and second frequency components of the input beam; coefficients B_1 and B_2 represent the amplitudes of background beams corresponding to reference beams A_1 and A_2, respectively; coefficients C_1 and C_2 represent the amplitudes of the return measurement beams corresponding to

reference beams A_1 and A_2, respectively; P_j represents the integrated intensity of the first frequency component of the input beam in pulse j of the pulse sequence; and the values for ε_j and γ_j are listed in Table 1. The change in the values of ε_j and γ_j from 1 to -1 or from -1 to 1 correspond to changes in relative phases of respective reference and measurement beams. The coefficients ξ_j, ζ_j, and η_j represent effects of variations in properties of a conjugate set of four pinholes such as size and shape used in the generation of the spot on and/or in substrate **60** and the sensitivities of a conjugate set of four detector pixels corresponding to the spot on and/or in substrate **60** for the reference beam, the background beam, and the return measurement beam, respectively. .

Table 1

j	ε_j	γ_j	$\varepsilon_j\gamma_j$
1	1	1	1
2	-1	-1	1
3	-1	1	-1
4	1	-1	-1

It is assumed in Equation (5) that the ratio of $|A_2|/|A_1|$ is not dependent on j or on the value of P_j. In order to simplify the representation of S_j so as to project the important features without departing from either the scope or spirit of the present invention, it is also assumed in Equation (5) that the ratio of the amplitudes of the return measurement beams corresponding to A_2 and A_1 is not dependent on j or on the value of P_j. However, the ratio $|C_2|/|C_1|$ will be different from the

ratio $|A_2|/|A_1|$ when the ratio of the amplitudes of the measurement beam components corresponding to A_2 and A_1 are different from the ratio $|A_2|/|A_1|$.

Noting that $\cos\varphi_{A_2C_2} = \pm\sin\varphi_{A_1C_1}$ by the control of the relative phase shifts between corresponding reference and return measurement beam components in beam **32**, Equation (5) may be rewritten as

$$S_j = P_j \left\{ \begin{array}{l} \xi_j^2\left(|A_1|^2 + |A_2|^2\right) + \zeta_j^2\left(|B_1|^2 + |B_2|^2\right) + \eta_j^2\left(|C_1|^2 + |C_2|^2\right) \\ +2\xi_j\zeta_j\left(|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_j} + |A_2||B_2|\cos\varphi_{A_2B_2\gamma_j}\right) \\ +2\xi_j\eta_j\left[\varepsilon_j|A_1||C_1|\cos\varphi_{A_1C_1} + \gamma_j\left(\dfrac{|A_2|}{|A_1|}\right)\left(\dfrac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\right] \\ +2\zeta_j\eta_j\left(\varepsilon_j|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_j} + \gamma_j|B_2||C_2|\cos\varphi_{B_2C_2\gamma_j}\right) \end{array} \right\} \quad (6)$$

where the relationship $\cos\varphi_{A_2C_2} = \sin\varphi_{A_1C_1}$ has been used without departing from either the scope or spirit of the present invention.

The change in phase $\varphi_{A_1B_1\varepsilon_j}$ $\varphi_{A_2B_2\gamma_j}$ for a change in ε_j and the change in phase $\varphi_{A_1B_1\varepsilon_j}$ $\varphi_{A_2B_2\gamma_j}$ for a change in γ_j may be different from π in embodiments depending on where and how the background beam is generated. It may be of value in evaluating the effects of the background beams to note that the factor $\cos\varphi_{B_1C_1\varepsilon_j}$ may be written as $\cos\left[\varphi_{A_1C_1} + \left(\varphi_{B_1C_1\varepsilon_j} - \varphi_{A_1C_1}\right)\right]$ where the phase difference $\left(\varphi_{B_1C_1\varepsilon_j} - \varphi_{A_1C_1}\right)$ is the same as the phase $\varphi_{A_1B_1\varepsilon_j}$, *i.e.*, $\cos\varphi_{B_1C_1\varepsilon_j} = \cos\left(\varphi_{A_1C_1} + \varphi_{A_1B_1\varepsilon_j}\right)$.

It is evident from inspection of Equation (6) that the term in Equation (6) corresponding to the component of conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ is a rectangular function that has a mean value of zero and is symmetric about $j = 2.5$

since ε_j is symmetric about $j = 2.5$. In addition the term in Equation (6) corresponding to the component of conjugated quadratures $|C_1|\sin\varphi_{A_1C_1}$ in Equation (6) is a rectangular function that has a mean value of zero and is antisymmetric about $j = 2.5$ since γ_j is a antisymmetric function about $j = 2.5$. Another important property by the design of the bi-homodyne detection method is that the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ terms are orthogonal over the range of $j = 1,2,3,4$ since ε_j and γ_j are orthogonal over the range of $j = 1,2,3,4$, *i.e.*, $\sum_{j=1}^{4} \varepsilon_j \gamma_j = 0$.

Information about conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ is obtained using the symmetric and antisymmetric properties and orthogonality property of the conjugated quadratures terms in Equation (6) as represented by the following digital filters applied to the signal values S_j:

$$
\begin{aligned}
F_1(S) = \sum_{j=1}^{4} \varepsilon_j \frac{S_j}{P_j' \xi_j'^2} &= \left(|A_1|^2 + |A_2|^2\right) \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^2}{\xi_j'^2}\right) \\
&+ \left(|B_1|^2 + |B_2|^2\right) \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^2}{\xi_j'^2}\right) + \left(|C_1|^2 + |C_2|^2\right) \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^2}{\xi_j'^2}\right) \\
&+ 2|A_1||C_1| \cos \varphi_{A_1 C_1} \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right) \\
&+ 2\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)|A_1||C_1| \sin \varphi_{A_1 C_1} \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right) \\
&+ 2|A_1||B_1| \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos \varphi_{A_1 B_1 \varepsilon_j} \\
&+ 2|A_2||B_2| \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos \varphi_{A_2 B_2 \gamma_j} \\
&+ 2|B_1||C_1| \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos \varphi_{B_1 C_1 \varepsilon_j} \qquad (7) \\
&+ 2|B_2||C_2| \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos \varphi_{B_2 C_2 \gamma_j} ,
\end{aligned}
$$

and

$$
\begin{aligned}
F_2(S) = \sum_{j=1}^{4} \gamma_j \frac{S_j}{P_j' \xi_j'^2} &= \left(|A_1|^2 + |A_2|^2\right) \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^2}{\xi_j'^2}\right) \\
&+ \left(|B_1|^2 + |B_2|^2\right) \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^2}{\xi_j'^2}\right) + \left(|C_1|^2 + |C_2|^2\right) \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^2}{\xi_j'^2}\right) \\
&+ 2|A_1||C_1| \cos \varphi_{A_1 C_1} \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right) \\
&+ 2\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)|A_1||C_1| \sin \varphi_{A_1 C_1} \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right) \\
&+ 2|A_1||B_1| \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos \varphi_{A_1 B_1 \varepsilon_j} \\
&+ 2|A_2||B_2| \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos \varphi_{A_2 B_2 \gamma_j} \\
&+ 2|B_1||C_1| \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos \varphi_{B_1 C_1 \varepsilon_j} \\
&+ 2|B_2||C_2| \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos \varphi_{B_2 C_2 \gamma_j}
\end{aligned}
\tag{8}
$$

where ξ_j' and P_j' are values used in the digital filters to represent ξ_j and P_j.

The parameter

$$
\left[\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\right] \tag{9}
$$

in Equations (7) and (8) needs to be determined in order complete the determination of a conjugated quadratures. The parameter given in Equation (9) can be measured

for example by introducing $\pi/2$ phase shifts into the relative phase of the reference beam and the measurement beam and repeating the measurement for the conjugated quadratures. The ratio of the amplitudes of the conjugated quadratures corresponding to $\left(\sin\varphi_{A_1C_1}/\cos\varphi_{A_1C_1}\right)$ from the first measurement divided by the ratio of the amplitudes of the conjugated quadratures corresponding to $\left(\sin\varphi_{A_1C_1}/\cos\varphi_{A_1C_1}\right)$ from the second measurement is equal to

$$\left[\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\right]^2. \tag{10}$$

Note that certain of the factors in Equations (7) and (8) have nominal values of 4 within scale factors, *e.g.*,

$$\sum_{j=1}^{4}\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\eta_j}{\xi_j'^2}\right)\simeq 4,\quad \sum_{j=1}^{4}\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j\eta_j}{\xi_j'^2}\right)\simeq 4. \tag{11}$$

The scale factors correspond to the average values for the ratios of ξ_j'/η_j and ξ_j'/ζ_j, respectively, assuming that the average value of $P_j/P_j' \cong 1$. Certain other of the factors in Equations (7) and (8) have nominal values of zero, *e.g.*,

$$\sum_{j=1}^{4}\varepsilon_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^{2}}{\xi_j'^{2}}\right)\simeq 0,\quad \sum_{j=1}^{4}\varepsilon_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^{2}}{\xi_j'^{2}}\right)\simeq 0,$$

$$\sum_{j=1}^{4}\varepsilon_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^{2}}{\xi_j'^{2}}\right)\simeq 0,$$

$$\sum_{j=1}^{4}\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^{2}}{\xi_j'^{2}}\right)\simeq 0,\quad \sum_{j=1}^{4}\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^{2}}{\xi_j'^{2}}\right)\simeq 0,$$

$$\sum_{j=1}^{4}\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^{2}}{\xi_j'^{2}}\right)\simeq 0,$$

$$\sum_{j=1}^{4}\varepsilon_j\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\eta_j}{\xi_j'^{2}}\right)\simeq 0. \tag{12}$$

The remaining factors,

$$\begin{gathered}
\sum_{j=1}^{4}\varepsilon_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\zeta_j}{\xi_j'^{2}}\right)\cos\varphi_{A_1B_1\varepsilon_j},\quad \sum_{j=1}^{4}\varepsilon_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\zeta_j}{\xi_j'^{2}}\right)\cos\varphi_{A_2B_2\gamma_j},\\
\sum_{j=1}^{4}\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j\eta_j}{\xi_j'^{2}}\right)\cos\varphi_{B_1C_1\varepsilon_j},\quad \sum_{j=1}^{4}\varepsilon_j\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j\eta_j}{\xi_j'^{2}}\right)\cos\varphi_{B_2C_2\gamma_j},\\
\sum_{j=1}^{4}\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\zeta_j}{\xi_j'^{2}}\right)\cos\varphi_{A_1B_1\varepsilon_j},\quad \sum_{j=1}^{4}\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\zeta_j}{\xi_j'^{2}}\right)\cos\varphi_{A_2B_2\gamma_j},\\
\sum_{j=1}^{4}\varepsilon_j\gamma_j\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j\eta_j}{\xi_j'^{2}}\right)\cos\varphi_{B_1C_1\varepsilon_j},\quad \sum_{j=1}^{4}\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j\eta_j}{\xi_j'^{2}}\right)\cos\varphi_{B_2C_2\gamma_j},
\end{gathered} \tag{13}$$

will have nominal magnitudes ranging from approximately zero to approximately 4 times a cosine factor and either the average value of factor

$\left(P_j/P_j'\right)\left(\xi_j\zeta_j/\xi_j'^2\right)$ or $\left(P_j/P_j'\right)\left(\zeta_j\eta_j/\xi_j'^2\right)$ depending on the properties respective phases. For the portion of the back ground with phases that do not track to a first approximation the phases of the measurement beams, the magnitudes of all of the terms listed in the Equation (13) will be approximately zero. For the portion of the background with phases that do track to a first approximation the phases of the respective measurement beams, the magnitudes of the terms listed in Equation (13) will be approximately 4 times a cosine factor and either the average value of factor $\left(P_j/P_j'\right)\left(\xi_j\zeta_j/\xi_j'^2\right)$ and or factor $\left(P_j/P_j'\right)\left(\zeta_j\eta_j/\xi_j'^2\right)$. .

The two largest terms in Equations (7) and (8) are generally the terms that have the factors $\left(|A_1|^2+|A_2|^2\right)$ and $\left(|B_1|^2+|B_2|^2\right)$. However, the corresponding terms are substantially eliminated by selection of ξ_j' values for the terms that have $\left(|A_1|^2+|A_2|^2\right)$ as a factor and by the design of ζ_j values for the terms that have $\left(|B_1|^2+|B_2|^2\right)$ as a factor as shown in Equation (12).

The largest contribution from effects of background is represented by the contribution to the interference term between the reference beam and the portion of the background beam generated by the measurement beam component of beam **28**. This portion of the effect of the background can be measured by measuring the corresponding conjugated quadratures of the portion of the background with the return measurement beam component of beam **32** set equal to zero, *i.e.*, measuring the respective electrical interference signals S_j with substrate **60** removed and with either $|A_2|=0$ or $|A_1|=0$ and visa versa. The measured conjugated quadratures of the portion of the effect of the background can than used to compensate for the respective background effects beneficially in an end use application if required.

Information about the largest contribution from effects of background amplitude $2\xi_j\zeta_j|A_1||B_1|$ and phase $\varphi_{A_1B_1\varepsilon_j}$, *i.e.*, the interference term between the reference beam and the portion of background beam generated by the measurement

beam component of beam **28**, may be obtained by measuring S_j for $j=1,2,3,4$ as a function of relative phase shift between reference beam and the measurement beam component of beam **28** with substrate **60** removed and either $|A_2|=0$ or $|A_1|=0$ and visa versa and Fourier analyzing the measured values of S_j. Such information can be used to help identify the origin of the respective background.

Other techniques may be incorporated into other embodiments to reduce and/or compensate for the effects of background beams without departing from either the scope or spirit of the present invention such as described in commonly owned U.S. Patent Nos. 5,760,901 entitled "Method And Apparatus For Confocal Interference Microscopy With Background Amplitude Reduction and Compensation," 5,915,048 entitled “Method and Apparatus for Discrimination In-Focus Images from Out-of- Focus Light Signals from Background and Foreground Light Sources,” and 6,480,285 B1 wherein each of the three patents are by Henry A. Hill. The contents of each of the three cited patents are herein incorporated in their entirety by reference.

The selection of values for ξ'_j is based on information about coefficients ξ_j for $j=1,2,3,4$ that may be obtained by measuring the S_j for $j=1,2,3,4$ with only the reference beam present in the interferometer system. In certain embodiments, this may correspond simply blocking the measurement beam components of input beam **24** and in certain other embodiments, this may correspond to simply measuring the S_j for $j=1,2,3,4$ with substrate **60** removed. A test of the correctness of a set of values for ξ'_j is the degree to which the $\left(|A_1|^2+|A_2|^2\right)$ terms in Equations (7) and (8) are zero.

Information about coefficients $\xi_j\eta_j$ for $j=1,2,3,4$ may be obtained by scanning an artifact past the spots corresponding to the respective four conjugate detector pixels with either $|A_2|=0$ or $|A_1|=0$ and measuring the conjugated quadratures component $2|A_1||C_1|\cos\varphi_{A_1C_1}$ or $2|A_1||C_1|\sin\varphi_{A_1C_1}$, respectively. A

change in the amplitude of the $2|A_1||C_1|\cos\varphi_{A_1C_1}$ or $2|A_1||C_1|\sin\varphi_{A_1C_1}$ term corresponds to a variation in $\xi_j\eta_j$ as a function of j. Information about the coefficients $\xi_j\eta_j$ for $j=1,2,3,4$ may be used for example to monitor the stability of one or more elements of interferometer system **10**.

The bi-homodyne detection method is a robust technique for the determination of conjugated quadratures of fields. First, the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ are the primary terms in the digitally filtered values $F_1(S)$ and $F_2(S)$, respectively, since as noted in the discussion with respect to Equation (12), the terms with the factors $\left(|A_1|^2+|A_2|^2\right)$ and $\left(|B_1|^2+|B_2|^2\right)$ are substantially zero.

Secondly, the coefficients of $|C_1|\cos\varphi_{A_1C_1}$ and $|C_2|\sin\varphi_{A_1C_1}$ terms in Equations (7) and (8) are identical. Thus highly accurate measurements of the interference terms between the return measurement beam and the reference beam with respect to amplitudes and phases, *i.e.*, highly accurate measurements of conjugated quadratures of fields can be measured wherein first order variations in ξ_j and first order errors in normalizations such as $\left(P_j/P'_j\right)$ and $\left(\xi_j^2/\xi_j'^2\right)$ enter in only second or higher order. This property translates into a significant advantage. Also, the contributions to each component of the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ from a respective set of four electrical interference signal values have the same window function and thus are obtained as jointly determined values.

Other distinguishing features of the bi-homodyne technique are evident in Equations (7) and (8): the coefficients of the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ in Equations (7) and (8), respectively, corresponding to the first equation of Equations (11) are identical independent of errors in assumed values for ξ_j and η_j; the coefficients of the conjugated quadratures $|C_1|\sin\varphi_{A_1C_1}$ and

$|C_1|\cos\varphi_{A_1C_1}$ in Equations (7) and (8), respectively, corresponding to the fourth equation of Equations (12) are identical independent of errors in assumed values for ξ_j'. Thus highly accurate values of the phases corresponding to conjugated quadratures can be measured with first order variations in ξ_j and first order errors in normalizations such as $\left(P_j/P_j'\right)$ and $\left(\xi_j^2/\xi_j'^2\right)$ enter in only through some high order effect.

It is also evident that since the conjugated quadratures of fields are obtained jointly when using the bi-homodyne detection method, there is a significant reduction in the potential for an error in tracking phase as a result of a phase redundancy unlike the situation possible in single-homodyne detection of conjugated quadratures of fields.

There are a number of advantages of the bi-homodyne detection as a consequence of the conjugated quadratures of fields being jointly acquired quantities. One advantage is a reduced sensitivity the effects of an overlay error of a spot in or on the substrate that is being imaged and a conjugate image of conjugate pixel of a multi-pixel detector during the acquisition of four electrical interference signal values of each spot in and/or on a substrate imaged using interferometric confocal microscopy. Overlay errors are errors in the set of four conjugate images of a respective set of conjugate detector pixels relative to the spot being imaged.

Another advantage is that when operating in the scanning mode there is a reduced sensitivity to effects of pinhole-to-pinhole variations in properties of a conjugate set of pinholes used in a confocal microscopy system that are conjugate to a spot in or on the substrate being imaged at different times during the scan.

Another advantage is that when operating in the scanning mode there is a reduced sensitivity to effects of pixel-to-pixel variation of properties within a set of conjugate pixels that are conjugate to a spot in or on the substrate being imaged at different times during the scan.

Another advantage is that when operating in the scanning mode there is reduced sensitivity to effects of pulse-to-pulse variations of a respective conjugate set of pulses of the input beam **24** to the interferometer system.

The pinholes and pixels of a multi-pixel detector of a set of conjugate pinholes and conjugate pixels of a multi-pixel detector may comprise contiguous pinholes of an array of pinholes and/or contiguous pixels of a multi-pixel detector or may comprise selected pinholes from an array of pinholes and/or pixels from an array of pixels wherein the separation between the selected pinholes is an integer number of pinhole separations and the separation between an array of respective pixels corresponds to an integer number of pixel separations without loss of lateral and/or longitudinal resolution and signal-to-noise ratios. The corresponding scan rate would be equal to the integer times the spacing of spots on the measurement object **60** conjugate to set of conjugate pinholes and/or set of conjugate pixels divided by the read out rate of the multi-pixel detector. This property permits a significant increase in through put for an interferometric confocal microscope with respect to the number of spots in and/or on a substrate imaged per unit time.

Referring to the quad-homodyne detection method, a set of four electrical interference signal values is obtained for each spot on and/or in substrate **60** being imaged with two pulse sequences from source **18** and beam-conditioner beam-conditioner **22**. The set of four electrical interference signal values $S_j,\ j=1,2,3,4$ used for obtaining conjugated quadratures of fields for a single a spot on and/or in a substrate being imaged is represented for the quad-homodyne detection within a scale factor by the formulae

$$S_1 = P_1 \left\{ \begin{array}{l} \xi_1^2|A_1|^2 + \zeta_1^2|B_1|^2 + \eta_1^2|C_1|^2 + \zeta_1\eta_1 2|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_1} \\ +\xi_1\zeta_1 2|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_1} + \varepsilon_1\xi_1\eta_1 2|A_1||C_1|\cos\varphi_{A_1C_1} \\ +\xi_1^2|A_2|^2 + \zeta_1^2|B_2|^2 + \eta_1^2|C_2|^2 + \zeta_1\eta_1 2|B_2||C_2|\cos\varphi_{B_2C_2\gamma_1} \\ +\xi_1\zeta_1 2|A_2||B_2|\cos\varphi_{A_2B_2\gamma_1} + \gamma_1\xi_1\eta_1 2|A_2||C_2|\cos\varphi_{A_2C_2} \end{array} \right\}, \qquad (14)$$

$$S_2 = P_1 \begin{Bmatrix} \xi_2^2 |A_3|^2 + \zeta_2^2 |B_3|^2 + \eta_2^2 |C_3|^2 + \zeta_2\eta_2 2|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_2} \\ +\xi_2\zeta_2 2|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_2} + \varepsilon_2\xi_2\eta_2 2|A_3||C_3|\cos\varphi_{A_3C_3} \\ +\xi_2^2 |A_4|^2 + \zeta_2^2 |B_4|^2 + \eta_2^2 |C_4|^2 + \zeta_2\eta_2 2|B_4||C_4|\cos\varphi_{B_4C_4\gamma_2} \\ +\xi_2\zeta_2 2|A_4||B_4|\cos\varphi_{A_4B_4\gamma_2} + \gamma_2\xi_2\eta_2 2|A_4||C_4|\cos\varphi_{A_4C_4} \end{Bmatrix}, \quad (15)$$

$$S_3 = P_2 \begin{Bmatrix} \xi_1^2 |A_1|^2 + \zeta_1^2 |B_1|^2 + \eta_1^2 |C_1|^2 + \zeta_1\eta_1 2|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_3} \\ +\xi_1\zeta_1 2|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_3} + \varepsilon_3\xi_1\eta_1 2|A_1||C_1|\cos\varphi_{A_1C_1} \\ +\xi_1^2 |A_2|^2 + \zeta_1^2 |B_2|^2 + \eta_1^2 |C_2|^2 + \zeta_1\eta_1 2|B_2||C_2|\cos\varphi_{B_2C_2\gamma_3} \\ +\xi_1\zeta_1 2|A_2||B_2|\cos\varphi_{A_2B_2\gamma_3} + \gamma_3\xi_1\eta_1 2|A_2||C_2|\cos\varphi_{A_2C_2} \end{Bmatrix}, \quad (16)$$

$$S_4 = P_2 \begin{Bmatrix} \xi_2^2 |A_3|^2 + \zeta_2^2 |B_3|^2 + \eta_2^2 |C_3|^2 + \zeta_2\eta_2 2|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_4} \\ +\xi_2\zeta_2 2|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_4} + \varepsilon_4\xi_2\eta_2 2|A_3||C_3|\cos\varphi_{A_3C_3} \\ +\xi_2^2 |A_4|^2 + \zeta_2^2 |B_4|^2 + \eta_2^2 |C_4|^2 + \zeta_2\eta_2 2|B_4||C_4|\cos\varphi_{B_4C_4\gamma_4} \\ +\xi_2\zeta_2 2|A_4||B_4|\cos\varphi_{A_4B_4\gamma_4} + \gamma_4\xi_2\eta_2 2|A_4||C_4|\cos\varphi_{A_4C_4} \end{Bmatrix}, \quad (17)$$

where coefficients A_1, A_2, A_3, and A_4 represent the amplitudes of the reference beams corresponding to the first, second, third, and fourth frequency components, respectively, of input beam **24**; coefficients B_1, B_2, B_3, and B_4 represent the amplitudes of background beams corresponding to reference beams A_1, A_2, A_3, and A_4, respectively; coefficients C_1, C_2, C_3, and C_4 represent the amplitudes of the return measurement beams corresponding to reference beams A_1, A_2, A_3, and A_4, respectively; P_1 and P_2 represent the integrated intensities of the first frequency component in the first and second pulse sequences, respectively, of the input beam **24**; and the values for ε_j and γ_j are listed in Table 1. The description of the coefficients ξ_j, ζ_j, and η_j for the quad-homodyne detection method is the same as

the corresponding portion of the description given for ξ_j, ζ_j, and η_j of the bi-homodyne detection method.

It is assumed in Equations (14), (15), (16), and (17) that the ratios of $|A_2|/|A_1|$ and $|A_4|/|A_3|$ are not dependent on j or the value of P_j. In order to simplify the representation of S_j so as to project the important features without departing from either the scope or spirit of the present invention, it is also assumed in Equations (14), (15), (16), and (17) that the ratios of the amplitudes of the return measurement beams corresponding to $|A_2|/|A_1|$ and $|A_4|/|A_3|$ are not dependent on j or the value of P_j. However, the ratios $|C_2|/|C_1|$ and $|C_4|/|C_3|$ will be different from the ratios $|A_2|/|A_1|$ and $|A_4|/|A_3|$, respectively, when the ratio of the amplitudes of the measurement beam components corresponding to $|A_2|/|A_1|$ and $|A_4|/|A_3|$, respectively, are different from the ratios $|A_2|/|A_1|$ and $|A_4|/|A_3|$, respectively.

Noting that $\cos\varphi_{A_2C_2} = \pm\sin\varphi_{A_1C_1}$ by the control of the relative phase shifts between corresponding reference and measurement beam components in beam **32**, Equations (14), (15), (16), and (17) may be written, respectively, as

$$S_1 = P_1 \left\{ \begin{array}{l} \xi_1^2\left(|A_1|^2 + |A_2|^2\right) + \zeta_1^2\left(|B_1|^2 + |B_2|^2\right) + \eta_1^2\left(|C_1|^2 + |C_2|^2\right) \\ +2\zeta_1\eta_1\left[|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_1} + |B_2||C_2|\cos\varphi_{B_2C_2\gamma_1}\right] \\ +2\xi_1\eta_1\left[\varepsilon_1|A_1||C_1|\cos\varphi_{A_1C_1} + \gamma_1\left(\dfrac{|A_2|}{|A_1|}\right)\left(\dfrac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\right] \\ +2\xi_1\zeta_1\left[|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_1} + |A_2||B_2|\cos\varphi_{A_2B_2\gamma_1}\right] \end{array} \right\}, \quad (18)$$

$$S_2 = P_1 \left\{ \begin{array}{l} \xi_2^2\left(|A_3|^2+|A_4|^2\right)+\zeta_2^2\left(|B_3|^2+|B_4|^2\right)+\eta_2^2\left(|C_3|^2+|C_4|^2\right) \\ +2\zeta_2\eta_2\left[|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_2}+|B_4||C_4|\cos\varphi_{B_4C_4\gamma_2}\right] \\ +2\xi_2\eta_2\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\left[\begin{array}{l} \varepsilon_2|A_1||C_1|\cos\varphi_{A_1C_1} \\ +\gamma_2\left(\frac{|A_4|}{|A_3|}\right)\left(\frac{|C_4|}{|C_3|}\right)|A_1||C_1|\sin\varphi_{A_1C_1} \end{array}\right] \\ +2\xi_2\zeta_2\left[|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_2}+|A_4||B_4|\cos\varphi_{A_4B_4\gamma_2}\right] \end{array} \right\}, \quad (19)$$

$$S_3 = P_2 \left\{ \begin{array}{l} \xi_1^2\left(|A_1|^2+|A_2|^2\right)+\zeta_1^2\left(|B_1|^2+|B_2|^2\right)+\eta_1^2\left(|C_1|^2+|C_2|^2\right) \\ +2\zeta_1\eta_1\left[|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_3}+|B_2||C_2|\cos\varphi_{B_2C_2\gamma_3}\right] \\ +2\xi_1\eta_1\left[\varepsilon_3|A_1||C_1|\cos\varphi_{A_1C_1}+\gamma_3\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\right] \\ +2\xi_1\zeta_1\left[|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_3}+|A_2||B_2|\cos\varphi_{A_2B_2\gamma_3}\right] \end{array} \right\}, \quad (20)$$

$$S_4 = P_2 \left\{ \begin{array}{l} \xi_2^2\left(|A_3|^2+|A_4|^2\right)+\zeta_2^2\left(|B_3|^2+|B_4|^2\right)+\eta_2^2\left(|C_3|^2+|C_4|^2\right) \\ +2\zeta_2\eta_2\left[|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_4}+|B_4||C_4|\cos\varphi_{B_4C_4\gamma_4}\right] \\ +2\xi_2\eta_2\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\left[\begin{array}{l} \varepsilon_4|A_1||C_1|\cos\varphi_{A_1C_1} \\ +\gamma_4\left(\frac{|A_4|}{|A_3|}\right)\left(\frac{|C_4|}{|C_3|}\right)|A_1||C_1|\sin\varphi_{A_1C_1} \end{array}\right] \\ +2\xi_2\zeta_2\left[|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_4}+|A_4||B_4|\cos\varphi_{A_4B_4\gamma_4}\right] \end{array} \right\}, \quad (21)$$

where the relationship $\cos\varphi_{A_2C_2}=\sin\varphi_{A_1C_1}$ has been used without departing from either the scope or spirit of the present invention.

Information about the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ are obtained using the symmetric and antisymmetric properties and orthogonality property of the conjugated quadratures as represented by the following digital filters applied to the signal values S_j: $j=1,2,3,4$

$$F_3(S)=\left(\frac{1}{P_1'}\right)\left(\frac{S_1}{\xi_1'^2}-\frac{S_2}{\xi_2'^2}\right)-\left(\frac{1}{P_2'}\right)\left(\frac{S_3}{\xi_1'^2}-\frac{S_4}{\xi_2'^2}\right), \tag{22}$$

$$F_4(S)=\left(\frac{1}{P_1'}\right)\left(\frac{S_1}{\xi_1'^2}-\frac{S_2}{\xi_2'^2}\right)+\left(\frac{1}{P_2'}\right)\left(\frac{S_3}{\xi_1'^2}-\frac{S_4}{\xi_2'^2}\right). \tag{23}$$

The description of ξ_j' and P_j' for the quad-homodyne detection method is the same as the corresponding description given for ξ_j' and P_j' in the bi-homodyne detection method. Using Equations (18), (19), (20), (21), (22), and (23), the following expressions are obtained for the filtered quantities containing components of the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$:

$$
\begin{aligned}
F_3(S) = & \left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(|A_1|^2 + |A_2|^2\right)\left(\frac{\xi_1^{\,2}}{\xi_1'^2}\right) - \left(|A_3|^2 + |A_4|^2\right)\left(\frac{\xi_2^{\,2}}{\xi_2'^2}\right)\right] \\
& + \left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(|B_1|^2 + |B_2|^2\right)\left(\frac{\zeta_1^{\,2}}{\xi_1'^2}\right) - \left(|B_3|^2 + |B_4|^2\right)\left(\frac{\zeta_2^{\,2}}{\xi_2'^2}\right)\right] \\
& + \left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(|C_1|^2 + |C_2|^2\right)\left(\frac{\eta_1^{\,2}}{\xi_1'^2}\right) - \left(|C_3|^2 + |C_4|^2\right)\left(\frac{\eta_2^{\,2}}{\xi_2'^2}\right)\right] \\
& + 2\left(\frac{P_1}{P_1'} + \frac{P_2}{P_2'}\right)\left[\left(\frac{\xi_1\eta_1}{\xi_1'^2}\right) + \left(\frac{\xi_2\eta_2}{\xi_2'^2}\right)\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\right]|A_1||C_1|\cos\varphi_{A_1C_1} \\
& + 2\left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\left[\begin{array}{l}\left(\dfrac{\xi_1\eta_1}{\xi_1'^2}\right) \\ +\left(\dfrac{\xi_2\eta_2}{\xi_2'^2}\right)\left(\dfrac{|A_4|}{|A_2|}\right)\left(\dfrac{|C_4|}{|C_2|}\right)\end{array}\right]|A_1||C_1|\sin\varphi_{A_1C_1} \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_1B_1\varepsilon_1} - \frac{P_2}{P_2'}\cos\varphi_{A_1B_1\varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|A_1||B_1| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_3B_3\varepsilon_2} - \frac{P_2}{P_2'}\cos\varphi_{A_3B_3\varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|A_3||B_3| \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_2B_2\gamma_1} - \frac{P_2}{P_2'}\cos\varphi_{A_2B_2\gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|A_2||B_2| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_4B_4\gamma_2} - \frac{P_2}{P_2'}\cos\varphi_{A_4B_4\gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|A_4||B_4| \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_1C_1\varepsilon_1} - \frac{P_2}{P_2'}\cos\varphi_{B_1C_1\varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|B_1||C_1| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_3C_3\varepsilon_2} - \frac{P_2}{P_2'}\cos\varphi_{B_3C_3\varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|B_3||C_3| \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_2C_2\gamma_1} - \frac{P_2}{P_2'}\cos\varphi_{B_2C_2\gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|B_2||C_2| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_4C_4\gamma_2} - \frac{P_2}{P_2'}\cos\varphi_{B_4C_4\gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|B_4||C_4|, \qquad (24)
\end{aligned}
$$

$$
\begin{aligned}
F_4(S) = {} & \left(\frac{P_1}{P_1'}+\frac{P_2}{P_2'}\right)\left[\left(|A_1|^2+|A_2|^2\right)\left(\frac{\xi_1{}^2}{\xi_1'^2}\right)-\left(|A_3|^2+|A_4|^2\right)\left(\frac{\xi_2{}^2}{\xi_2'^2}\right)\right] \\
& +\left(\frac{P_1}{P_1'}+\frac{P_2}{P_2'}\right)\left[\left(|B_1|^2+|B_2|^2\right)\left(\frac{\zeta_1{}^2}{\xi_1'^2}\right)-\left(|B_3|^2+|B_4|^2\right)\left(\frac{\zeta_2{}^2}{\xi_2'^2}\right)\right] \\
& +\left(\frac{P_1}{P_1'}+\frac{P_2}{P_2'}\right)\left[\left(|C_1|^2+|C_2|^2\right)\left(\frac{\eta_1{}^2}{\xi_1'^2}\right)-\left(|C_3|^2+|C_4|^2\right)\left(\frac{\eta_2{}^2}{\xi_2'^2}\right)\right] \\
& +2\left(\frac{P_1}{P_1'}-\frac{P_2}{P_2'}\right)\left[\left(\frac{\xi_1\eta_1}{\xi_1'^2}\right)+\left(\frac{\xi_2\eta_2}{\xi_2'^2}\right)\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\right]|A_1||C_1|\cos\varphi_{A_1C_1} \\
& +2\left(\frac{P_1}{P_1'}+\frac{P_2}{P_2'}\right)\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\left[\begin{array}{l}\left(\dfrac{\xi_1\eta_1}{\xi_1'^2}\right) \\ +\left(\dfrac{\xi_2\eta_2}{\xi_2'^2}\right)\left(\dfrac{|A_4|}{|A_2|}\right)\left(\dfrac{|C_4|}{|C_2|}\right)\end{array}\right]|A_1||C_1|\sin\varphi_{A_1C_1} \\
& +2\left(\frac{P_1}{P_1'}\cos\varphi_{A_1B_1\varepsilon_1}+\frac{P_2}{P_2'}\cos\varphi_{A_1B_1\varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|A_1||B_1| \\
& -2\left(\frac{P_1}{P_1'}\cos\varphi_{A_3B_3\varepsilon_2}+\frac{P_2}{P_2'}\cos\varphi_{A_3B_3\varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|A_3||B_3| \\
& +2\left(\frac{P_1}{P_1'}\cos\varphi_{A_2B_2\gamma_1}+\frac{P_2}{P_2'}\cos\varphi_{A_2B_2\gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|A_2||B_2| \\
& -2\left(\frac{P_1}{P_1'}\cos\varphi_{A_4B_4\gamma_2}+\frac{P_2}{P_2'}\cos\varphi_{A_4B_4\gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|A_4||B_4| \\
& +2\left(\frac{P_1}{P_1'}\cos\varphi_{B_1C_1\varepsilon_1}+\frac{P_2}{P_2'}\cos\varphi_{B_1C_1\varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|B_1||C_1| \\
& -2\left(\frac{P_1}{P_1'}\cos\varphi_{B_3C_3\varepsilon_2}+\frac{P_2}{P_2'}\cos\varphi_{B_3C_3\varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|B_3||C_3| \\
& +2\left(\frac{P_1}{P_1'}\cos\varphi_{B_2C_2\gamma_1}+\frac{P_2}{P_2'}\cos\varphi_{B_2C_2\gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|B_2||C_2| \\
& -2\left(\frac{P_1}{P_1'}\cos\varphi_{B_4C_4\gamma_2}+\frac{P_2}{P_2'}\cos\varphi_{B_4C_4\gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|B_4||C_4|. \qquad (25)
\end{aligned}
$$

The parameters

$$\left[\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\right], \tag{26}$$

$$\left(\frac{|A_4|}{|A_2|}\right)\left(\frac{|C_4|}{|C_2|}\right), \tag{27}$$

$$\left[\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\right] \tag{28}$$

need to be determined in order to complete the determination of a conjugated quadratures for certain end use applications. The parameters given by Equations (26), (27), and (28) can for example be measured by procedures analogous to the procedure described for the bi-homodyne detection method with respect to measuring the quantity specified by Equation (9).

The remaining description of the quad-homodyne detection method is the same as corresponding portion of the description given for the bi-homodyne detection method.

It is also evident that since the conjugated quadratures of fields are obtained jointly when using the quad-homodyne detection, there is a significant reduction in the potential for an error in tracking phase as a result of a phase redundancy unlike the situation possible in single-homodyne detection of conjugated quadratures of fields.

There are a number of advantages of the quad-homodyne detection as a consequence of the conjugated quadratures of fields being jointly acquired quantities.

One advantage is a reduced sensitivity the effects of an overlay error of a spot in or on the substrate that is being imaged and a conjugate image of a pixel of a

conjugate set of pixels of a multi-pixel detector during the acquisition of the four electrical interference signal values of each spot in and/or on a substrate imaged using interferometric confocal microscopy. Overlay errors are errors in the set of four conjugate images of a respective set of conjugate detector pixels relative to the spot being imaged.

Another advantage is that when operating in the scanning mode there is reduced sensitivity to effects of pulse-to-pulse variations of a respective conjugate set of pulses of the input beam **24** to the interferometer system.

Another advantage is that when operating in the scanning mode there is an increase in through-put since only one pulse of the source is required to generate the at least four electrical interference values.

A first embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** of the first embodiment that is shown schematically in Fig. **2a**. Interferometer **10** comprises an interferometer such as described in commonly owned U.S. Provisional Patent Application filed No. 60/447,254 (ZI-40) entitled "Transverse Differential Interferometric Confocal Microscopy" and U.S Patent Application filed February , 2004 (ZI-40) also entitled "Transverse Differential Interferometric Confocal Microscopy" both of which are by Henry A. Hill. The contents of the U.S. Provisional Patent Application and the U.S. Patent Application are herein incorporated in their entirety by reference.

Interferometer **10** of the first embodiment comprises a first imaging system generally indicated as numeral **110**, pinhole array beam-splitter **112**, detector **70**, and a second imaging system generally indicated as numeral **210**. The second imaging system **210** is low power microscope having a large working distance, *e.g.* Nikon ELWD and SLWD objectives and Olympus LWD, ULWD, and ELWD objectives. The first imaging system **110** comprises an interferometric confocal microscopy system described in part in commonly owned U.S. Provisional Application No. 60/442,982 (ZI-45) entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter" and U.S. Patent Application No. _______filed January 27, 2004 (ZI-45) and also entitled "Interferometric Confocal

Microscopy Incorporating Pinhole Array Beam-Splitter" both of which are by Henry A. Hill. The contents of both of the U.S. Provisional Patent Application and the U.S. Patent Application are herein incorporated in their entirety by reference.

First imaging system **110** is shown schematically in Fig. **2b**. The imaging system **110** is a catadioptric system such as described in commonly owned U.S. Patent No. 6,552,852 B2 (ZI-38) entitled "Catoptric and Catadioptric Imaging System" and commonly owned U.S. Patent Application No. 10/366,651 (ZI-43) entitled "Catoptric And Catadioptric Imaging Systems" wherein both of the patent applications are by Henry A. Hill, the contents of the two cited patent applications incorporated herein in their entirety by reference.

Catadioptric imaging system **110** comprises catadioptric elements **140** and **144**, beam-splitter **148**, and convex lens **150**. Surfaces **142B** and **146B** are concave spherical surfaces with nominally the same radii of curvature and the centers of curvature of surfaces **142B** and **146B** are conjugate points with respect to beam-splitter **148**. Surfaces **142A** and **142C** are convex spherical surfaces that have the same centers of curvature and surfaces **146A** and **146C** are convex spherical surfaces that have the same centers of curvature. Surfaces **142A**, **142C**, **146A**, and **146C** nominally have the same radii of curvature. The centers of curvature of surfaces **142A** and **142C** are shifted by a small displacements $\left(0,0,z_1'\right)$ with respect to beam-splitter **148** or equivalently to the centers of curvature of surfaces **146B** and surfaces **146A** and **146C** are shifted by a small displacements $\left(0,0,-z_2'\right)$ with respect to the centers of curvature of surfaces **142B**. Relative displacements $\left(0,0,z_1'\right)$ and $\left(0,0,z_2'\right)$ are selected to optimize the performance of interferometer **10** with respect to acquisition of information about substrate **60**. The center of curvature of convex lens **150** is the same as the center of curvature of surfaces **142B**. The radius of curvature of surface **146B** is selected so as to minimize the loss in usable solid angle of the imaging system **110** and to produce a working distance for imaging system **110** acceptable for an end use application, *e.g.*, of the order of a

mm. The radius of curvature of convex lens **150** is selected so that off-axis aberrations of the catadioptric imaging system **110** are compensated. The medium of elements **140** and **144** may be for example CaF_2, fused silica or commercially available glass such as SF11. The medium of convex lens **150** may be for example CaF_2, fused silica, YAG, or commercially available glass such as SF11. An important consideration in the selection of the media of elements **140** and **144** and convex lens **150** will the transmission properties for the frequencies of beam **24**.

Note that as a result of the small displacements just mentioned, the conjugate of the center of curvature of surface **142A**, as seen through beam splitter **148**, does not coincide with the center of curvature of surface **146A**. (Or, equivalently, the conjugate of the center of curvature of surface **146A**, as seen through beam splitter **148**, does not coincide with the center of curvature of surface **142A**.) Rather, those two points are displaced by an amount determined by the small displacement of the two surfaces **142A** and **146A** relative to each other. The direction of their displacement relative to each other is normal to the plane of beam splitter **148**.

Convex lens **152** has a center of curvature the same as the center of curvature of convex lens **150**. Convex lenses **150** and **152** are bonded together with pinhole beam-splitter **112** in between. Pinhole array beam-splitter **112** is shown in Fig. **2c**. The pattern of pinholes in pinhole array beam-splitter is chosen to match the requirements of an end use application. An example of a pattern is a two dimensional array of equally spaced pinholes in two orthogonal directions. The pinholes may comprise circular apertures, rectangular apertures, or combinations thereof such as described in commonly owned U.S. Patent Application No. 09/917,402 (ZI-15) entitled "Multiple-Source Arrays for Confocal and Near-field Microscopy" by Henry A. Hill and Kyle Ferrio of which the contents thereof are incorporated herein in their entirety by reference. The spacing between pinholes of pinhole array beam-splitter **112** is shown in Fig. **2c** as b with aperture size a.

Input beam **24** is reflected by mirror **54** to pinhole beam-splitter **112** where a first portion thereof is transmitted as reference beam components of output beam components **130A** and **130B** (see Fig. **2a**) and a second portion thereof scattered as

measurement beam components of beam components **126A** and **126B**. The measurement beam components of beam components **126A** and **126B** are imaged as measurement beam components of beam components **128A** and **128B** to an array of image spots in image planes displaced from the surface of substrate **60**.

The arrays of image spots in the image planes displaced from the surface of substrate **60** comprises a first and second array of image spots with the second array of image spots transversely and longitudinally displaced with respect to the first array of image spots. The locations of a corresponding pair of spots **164** and **166** of the first and second arrays of image spots are shown diagrammatically in Figs. **2d** and **2e** for the case where the displacements $z_1' = z_2'$ of convex surfaces **142A**, **142C**, **146A**, and **146C**. The corresponding pair of spots **164** and **166** are images of a pinhole **162** in of pinhole array beam-splitter **112**. The displacement of center of curvature of surface **142A** is in the positive z direction. An example of a path of a beam contributing to image spot **164** is beam **126E** and an example of a path of a beam contributing to image spot **166** is beam **126F** (see Fig. **2d**).

A portion of beam **126E** is also reflected twice by beam-splitter **148** and once by convex surfaces **142A** and **142C** to form an image spot **184** (see Fig. **2d**) at location $(-x_1/n, -y_1/n, -2z_1/n)$ of pinhole **162** where x_1 and y_1 are the x and y coordinates, respectively, of pinhole **162** in the plane of pinhole array beam-splitter **112** and n is the index of refraction of convex lenses **150** and **152**. In addition, a portion of beam **126F** is transmitted twice by beam-splitter **148** and reflected once by convex surfaces **146A** to form an image spot **186** (see Fig. **2d**) at location $(-x_1/n, -y_1/n, 2z_2/n)$. The locations of image spots **184** and **186** are arranged to be half way between pinholes of pinhole array beam-splitter **112** by selecting the location of pinhole **162** relative to the location of the center of curvatures of lenses **150** and **152** to be either $b/4 \bmod b$ or $(3/4)b \bmod b$.

Next consider the affects of catadioptric imaging system **110** on reflected portions of the beams comprising image spots **164** and **166** by the surface of substrate **60**. The reflected portions are part of the return measurement beam

components of beams **128A** and **128B** and imaged by catadioptric imaging system **110** to four spots **190**, **192**, **194**, and **196** in the space of pinhole array beam-splitter **112** (see Fig. **2e**). The locations of the respective spots with respect to the pinhole source of beams **126E** and **126F** are $\left[x_1, y_1, (2h_1 - 4z_1)/n\right]$, $\left[x_1, y_1, (2h_1 + 4z_2)/n\right]$, $\left[x_1/n, y_1/n, 2(h_1 - z_1 + z_2)/n\right]$, and $\left[x_1/n, y_1/n, 2(h_1 - z_1 + z_2)/n\right]$ where $2z_1 - h_1$ and $-2z_2 + h_1$ are the displacements of spots **164** and **166** from the surface of substrate **60**, respectively.

Portions of the beams forming image spots **190**, **192**, **194**, and **196** are transmitted by the pinhole corresponding to pinhole source of beams **126E** and **126F** as a component of beam components **130A** and **130B**. The beams forming image spots **184** and **186** are not transmitted by the pinhole corresponding to the pinhole source of beams **126E** and **126F** or by other pinholes of pinhole array beam-splitter **112** because of the displacements of image spots **184** and **186** with respect to the pinhole corresponding to pinhole source of beams **126E** and **126F** and because of the displacement relative to other pinholes that is generated as a result of the selection of the pinhole locations of pinhole array beam-splitter **112** relative to the center of curvatures of lenses **150** and **152** to be either $b/4 \bmod b$ or $(3/4)b \bmod b$. To further reduce the effects of spurious beams generated by reflection of portions of the beams forming image spots **184** and **186** by pinhole array beam-splitter **112**, the respective surface of pinhole array beam-splitter **112** is coated with an anti-reflective coating.

The effects of spurious beams generated by reflection of portions of the beams forming image spots **184** and **186** by pinhole array beam-splitter **112** are further reduced since the array of image spots **184**, **186**, **190**, **192**, **194**, and **196** form only two superimposed images on the $x-y$ plane.

The description of the affects of catadioptric imaging system **110** on portions of the beams comprising image spots **164** and **166** that are scattered by sub-wavelength artifacts and/or defects on the surface of substrate **60** is based on an analysis that is a variant of the analysis forming the basis of the description given

for the affects of catadioptric imaging system **110** on the portions of the beams comprising image spots **164** and **166** that are reflected by the surface of substrate **60**.

The next step is the imaging of output beam components **130A** and **130B** by imaging system **210** to an array of spots that coincide with the pixels of a multi-pixel detector **70** such as a CCD to generate an array of electrical interference signals **72**. The array of electrical interference signals is transmitted to signal processor and controller **80** for subsequent processing for an array of conjugated quadratures.

The description of input beam **24** is the same as corresponding portions of the description given for input beam **24** of Fig. **1a** with beam-conditioner **22** configured as a two-frequency generator and frequency-shifter shown in Fig. **1c**. Input beam **24** comprises two components that have different frequencies and have the same state of plane polarization. The frequency of each component of input beam **24** is shifted between different frequency values by beam-conditioner **22** according to control signal **74** generated by electronic processor and controller **80**. Beam **20** comprises single frequency component.

The conjugated quadratures of fields of the return measurement beams are obtained using the bi-homodyne detection method wherein sets of four measurements of the electrical interference signals **72** are made. An array of conjugated quadratures of fields is measured interferometrically by interferometer confocal imaging system **10** wherein each conjugated quadratures comprises a difference of conjugated quadratures of fields of beams scattered/reflected from a pair of spots in or on a substrate. The array of conjugated quadratures is measured jointly, *i.e.*, simultaneously, and the components of each conjugated quadratures are measured jointly.

The relative phases of the beams subsequently scattered/reflected by the pair of spots in or on a substrate are adjusted by the control of interferometer system parameters, *e.g.*, the relative optical path lengths of measurement and return measurement beam components corresponding to respective spots of the pairs of spots in or on substrate **60**. The relative phases are adjusted by making changes in

the radii of curvature of convex surfaces **142A**, **142C**, **146A**, and **146C** without introducing changes in the respective centers of curvature. An example of a technique to introduce a change in a radii of curvature of the convex surfaces of **142A**, **142C**, **146A**, and **146C** is to add uniform layers to the respective surfaces comprising an index of refraction matching material. Another example of a technique to introduce a change in relative phase is to add a concave reflecting surface next to a convex surface with an air gap such that the air gap thickness may be adjusted. In the latter example, the convex would be anti-reflective coated.

The measured conjugate quadratures in the first embodiment are proportional to components of complex amplitude $V_3\left(h_1, z_1, h_2, z_2, \chi_1, \chi_2, \chi_{3,}\chi_4\right)$ that can to a good approximation be written as

$$
\begin{aligned}
&V_3\left(h_1, z_1, h_2, z_2, \chi_1, \chi_2, \chi_{3,}\chi_4\right) = R_1^{1/2} e^{-i2\beta_0 h_1} \\
&\times\left(\left(\begin{array}{l}
j_0\left[2\alpha_0\left(h_1 - 2z_1\right)\right] e^{i4\beta_0 z_1 + i(\chi_1+\chi_2)} \\
+ j_0\left[2\alpha_0\left(h_1 + 2z_2\right)\right] e^{-i4\beta_0 z_2 + i(\chi_3+\chi_4)} \\
+ j_0\left\{2\alpha_0\left[h_1 + \left(z_1 - z_2\right)\right]\right\} e^{i2\beta_0(z_1-z_2) + i(\chi_1+\chi_4)} \\
+ j_0\left\{2\alpha_0\left[h_1 + \left(z_1 - z_2\right)\right]\right\} e^{i2\beta_0(z_1-z_2) + i(\chi_2+\chi_3)}
\end{array}\right)\right) \\
&- R_1^{1/2} e^{-i2\beta_1 h_1}\left(\frac{1-\cos\theta_1}{1-\cos_0}\right)^{1/2} \\
&\times\left(\left(\begin{array}{l}
j_0\left[2\alpha_1\left(h_1 - 2z_1\right)\right] e^{i4\beta_1 z_1 + i(\chi_1+\chi_2)} \\
+ j_0\left[2\alpha_1\left(h_1 + 2z_2\right)\right] e^{-i4\beta_1 z_2 - i(\chi_3+\chi_4)} \\
+ j_0\left\{2\alpha_1\left[h_1 + \left(z_1 - z_2\right)\right]\right\} e^{i2\beta_1(z_1-z_2) + i(\chi_1+\chi_4)} \\
+ j_0\left\{2\alpha_1\left[h_1 - \left(z_1 - z_2\right)\right]\right\} e^{+i2\beta_1(z_1-z_2) + i(\chi_2+\chi_3)}
\end{array}\right)\right)
\end{aligned}
\qquad (29)
$$

where $R_1^{1/2}$ is the complex reflectivity coefficient of the surface of substrate **60** for the fields of the beams forming spots **164** and **166**; χ_1, χ_2, χ_3, and χ_4 are the

phase shifts introduced by changing the radii of curvature of convex surfaces **142A**, **142C**, **146A**, and **146C**, respectively, while maintaining the respective centers of curvatures constant;

$$\alpha_0 = k(1-\cos\theta_0); \tag{30}$$

$$\alpha_1 = k(1-\cos\theta_1); \tag{31}$$

$$\beta_0 = k(1+\cos\theta_0); \tag{32}$$

$$\beta_1 = k(1+\cos\theta_1); \tag{33}$$

$j_p(x)$ is the spherical Bessel function of order $p = 0,1,2,\ldots$; and $\sin\theta_0$ and $\sin\theta_1$ are the numerical apertures, respectively, of the imaging system without an occulting aperture and of the occulted aperture in the image space of substrate **60**. Descriptions of derivations that form the basis for the two terms in Equation (29) may be found in references such as the book edited by T. Wilson, *Confocal Microscopy*, Academic Press (1990), the contents of which are herein incorporated in their entirety by reference.

The form in which Equation (29) is written reflects certain important aspects of the first embodiment: the pinhole sources for each of the beams forming spots **164** and **166** (see Fig. **2d**) are the same pinhole of pinhole array beam-splitter **112**, the pinholes performing the confocal spatial filtering of the beams forming spots **190**, **192**, **194**, and **196** are the same pinhole of pinhole array beam-splitter **112** (see Figs. **2c** and **2e**), and the portions of the beams forming spots **190**, **192**, **194**, and **196** subsequently spatially filtered, *i.e.*, transmitted, by the same pinhole are detected by the same pixel of detector **70**.

In the first embodiment, phases χ_1, χ_2, χ_3, and χ_4 are selected such that beams **194** and **196** are out of phase by π and thus destructively interfere with each other. Corresponding conditions placed on phases χ_1, χ_2, χ_3, and χ_4 are

$$(\chi_1+\chi_4)-(\chi_2+\chi_3)=\pm\pi,\pm3\pi,\pm5\pi,\ldots, \tag{34}$$

With a non-limiting assumptions that $y_1=0$, and $z_1=z_2$, Equation (29) assumes the form

$$\begin{aligned}
V_3\left(h_1,z_1,h_1,z_1,\chi_1,\chi_2,\chi_3,\chi_4\right) &= R_1^{1/2}e^{-i2\beta_0 h_1} \\
&\times\left\{\begin{array}{l} j_0\left[2\alpha_0\left(h_1-2z_1\right)\right]e^{i4\beta_0 z_1+i(\chi_1+\chi_2)} \\ +j_0\left[2\alpha_0\left(h_1+2z_1\right)\right]e^{-i4\beta_0 z_1+i(\chi_3+\chi_4)}\end{array}\right\} \\
&-R_1^{1/2}e^{-i2\beta_1 h_1}\left(\frac{1-\cos\theta_1}{1-\cos_0}\right)^{1/2} \\
&\times\left\{\begin{array}{l} j_0\left[2\alpha_1\left(h_1-2z_1\right)\right]e^{i4\beta_1 z_1+i(\chi_1+\chi_2)} \\ +j_0\left[2\alpha_1\left(h_1+2z_1\right)\right]e^{-i4\beta_1 z_1+i(\chi_3+\chi_4)}\end{array}\right\}.
\end{aligned} \tag{35}$$

The first embodiment is further configured to operate in the dark field mode when $h_1\cong 0$. The dark field requirement is achieved by placing a second condition on the phases χ_1, χ_2, χ_3, and χ_4 in conjunction with a condition on z_1. The second condition is

$$(\chi_1+\chi_2)-(\chi_3+\chi_4)=0,\pm2\pi,\pm4\pi,\ldots. \tag{36}$$

The two conditions on phases χ_1, χ_2, χ_3, and χ_4 represented by Equations (34) and (36) are combined to obtain relationships between pair of phases χ_1, χ_2, χ_3, and χ_4, *e.g.*,

$$\chi_1 - \chi_3 = \pm\frac{\pi}{2} + p2\pi\,, |p| = 0,1,2,\ldots, \tag{37}$$

$$\chi_2 - \chi_4 = \mp\frac{\pi}{2} + q2\pi\,, |q| = 0,1,2,\ldots. \tag{38}$$

For the conditions $\chi_1 - \chi_3 = \frac{\pi}{2}$ and $\chi_2 - \chi_4 = -\frac{\pi}{2}$, Equation (35) reduces to

$$\begin{aligned} V_3(h_1, z_1, h_1, z_1, \chi_1, \chi_2, \chi_1 - \pi/2, \chi_2 + \pi/2) &= R_1^{1/2} e^{-i2\beta_0 h_1} e^{i(\chi_1 + \chi_2)} \\ &\times \left\{ \begin{array}{l} j_0\left[2\alpha_0 (h_1 - 2z_1)\right] e^{i4\beta_0 z_1} \\ + j_0\left[2\alpha_0 (h_1 + 2z_1)\right] e^{-i4\beta_0 z_1} \end{array} \right\} \\ &- R_1^{1/2} e^{-i2\beta_1 h_1} \left(\frac{1 - \cos\theta_1}{1 - \cos_0} \right)^{1/2} e^{i(\chi_1 + \chi_2)} \\ &\times \left\{ \begin{array}{l} j_0\left[2\alpha_1 (h_1 - 2z_1)\right] e^{i4\beta_1 z_1} \\ + j_0\left[2\alpha_1 (h_1 + 2z_1)\right] e^{-i4\beta_1 z_1} \end{array} \right\}. \end{aligned} \tag{39}$$

Using a contracted notation of $V_3(h_1, z_1, h_1, z_1, \chi_1, \chi_2, \chi_1 - \pi/2, \chi_2 + \pi/2) = V_3(h_1, z_1)$ and making a power series expansion of Equation (39) in h_1, we have

$$
\begin{aligned}
V_3(h_1, z_1) &= 2R_1^{1/2} e^{i(\chi_1+\chi_2)} \\
&\times \left[j_0(4\alpha_0 z_1)\cos 4\beta_0 z_1 - \left(\frac{1-\cos\theta_1}{1-\cos\theta_0}\right)^{1/2} j_0(4\alpha_1 z_1)\cos 4\beta_1 z_1 \right] \\
&+ i2R_1^{1/2} e^{i(\chi_1+\chi_2)} \\
&\times \left[j_1(4\alpha_0 z_1)\sin 4\beta_0 z_1 - \left(\frac{1-\cos\theta_1}{1-\cos\theta_0}\right)^{1/2} \frac{\alpha_1}{\alpha_0} j_1(4\alpha_1 z_1)\sin 4\beta_1 z_1 \right] 2\alpha_0 h_1 \\
&- i2R_1^{1/2} e^{i(\chi_1+\chi_2)} \\
&\times \left[j_0(4\alpha_0 z_1)\cos 4\beta_0 z_1 - \left(\frac{1-\cos\theta_1}{1-\cos\theta_0}\right)^{1/2} \frac{\beta_1}{\beta_0} j_0(4\alpha_1 z_1)\cos 4\beta_1 z_1 \right] 2\beta_0 h_1 \\
&+ \ldots .
\end{aligned}
\tag{40}
$$

The dark field mode of operation of the first embodiment is achieved by selecting a value of z_1 such that the constant term in Equation (40) is zero. The selected values for z_1 are solutions of the transcendental equation

$$
j_0(4\alpha_0 z_1)\cos 4\beta_0 z_1 = \left(\frac{1-\cos\theta_1}{1-\cos\theta_0}\right)^{1/2} j_1(4\alpha_1 z_1)\cos 4\beta_1 z_1 . \tag{41}
$$

A set of solutions of the transcendental equation $\alpha_0 z_{1,m}$, $m = 1,2,$ and 3, for the example of $\theta_0 = 60$ degrees and $\theta_1 = 15$ degrees is listed in Table 2. Also listed in Table 2 are the corresponding sizes D_m, full width at half maximum, of the common spots relative to the diffraction-limited resolution $\lambda/2NA$ of the interferometric confocal imaging system.

When the transcendental equation of Equation (41) is satisfied, fields of beams **194** and **196** at pinhole array beam-splitter **112** are equal in magnitude and have opposite phases. There will be out-of-phase spurious beams generated that are out of phase by 180 degrees as a result of the destructive interference of fields of

beams **194** and **196**. It is apparent that a portion of the out of phase spurious beams will generate out-of-phase secondary spurious beams that are focused to spots near pinhole **162** in an manner analogous to the generation of spots **190, 192, 194,** and **196**. The amplitudes of the effects of the secondary spurious beams will be less than or of the order of 5% of the amplitudes of the portions of the beams forming spots **190** and **192** transmitted by the corresponding pinhole in pinhole array **112** and will in first order effect the level of the dark field and only in second order the sensitivity to height measurements.

The important feature of Equation (40) is that the definition of the height of the surface of substrate **60** corresponds to a vertical position of substrate **60** such that $V_3(h_1, z_1) = 0$, *i.e.*, such that values of the corresponding conjugated quadratures is zero. The coefficients of h_1 in Equation (40) may be measured as a function of properties of materials. Corresponding values of the coefficients of h_1 in Equation (40) are listed in Table 2 as $\partial V_3(h_1, z_{1,m})/\partial h_1$. The first embodiment may be operated in a scanning mode and measured arrays of conjugated quadratures

Table 2

m	$\alpha_0 z_{1,m}$	$\dfrac{2z_{1,m}}{\lambda}$	$\dfrac{\partial V_3(h_1, z_{1,m})}{\partial h_1}\left(\dfrac{1}{iR_1^{1/2}}\right)$	$\dfrac{D_m}{\left(\dfrac{\lambda}{2NA}\right)}$
1	0.2628	0.0837	0.690	1.119
2	0.8252	0.2627	-1.216	1.867
3	1.3424	0.4273	0.849	2.752

may be converted to a height profile by using the measured properties of the coefficients of h_1, *i.e.*, it is not necessary to scan in h_1 in order to determine the height of the surface relative to a reference frame.

It is important to note that the use of the $m=1$ solution listed in Table 2 in an end use application will permit the examination of substrate **60** essentially with a diffraction-limited resolution. This feature of the first embodiment represents an important advantage. Alternatively, the use of the $m=2$ solution in Table 2 in an end use application will permit the examination of substrate **60** with an increase in sensitivity of approximately 1.8 compared to the sensitivity of the $m=1$ solution but at the expense of lateral spatial resolution.

Operation in a dark field mode leads to both reduced systematic and statistical errors in the information represented by the arrays of conjugated quadratures and increased throughput. The information may comprise the transverse derivative of a profile of one or more surfaces of substrate **60** in or on substrate **60**; one-dimensional, two-dimensional, and three-dimensional transverse differential images of substrate **60**; critical dimensions of features or artifacts on or in substrate **60**, and the sizes and locations of sub-wavelength defects in or on substrate **60**.

The background components of return measurement beams generated by scattering/reflection of measurement beam components by conjugate spots are the same and therefore do not contribute to the electrical interference signals **72**. Accordingly, the background components do not contribute to either the average values of the electrical interference signals **72** or to interference terms in electrical interference signals **72** for both the first and second embodiments.

The reduction of statistical error is also a direct consequence of operation in the dark field mode. The contributions of background fields are removed/eliminated in the second embodiment by the superposition of background fields arranged to have the same amplitudes and phase differences of π and not by the subtraction of intensities. As a result of the dark field, the intensity of beam **24** can be increased significantly without saturation of detector **70** and a corresponding reduction in statistical error is achieved.

The increase in throughput is a direct consequence of operating in a dark field mode. The time required to achieve a certain precision in the measured array

of conjugated quadratures is reduced by an increase of the intensity of beam **24** that is permitted by operating in the dark field mode. As a result of the dark field, the intensity of beam **24** can be increased significantly without saturation of detector **70**.

Also when operating in a dark field mode, a measured conjugated quadratures of fields corresponding to a pair of spots comprising a sub-wavelength artifact in a locally isotropic section of substrate **60** represents information about the sub-wavelength artifact relative to a reference sub-wavelength artifact. The reference sub-wavelength artifact has properties of the locally isotropic section and dimensions similar to those of the artifact. Accordingly, properties measured include information about critical dimensions and location of the sub-wavelength artifact in or on substrate **60**.

Also when operating in a dark field mode, a measured conjugated quadratures of fields corresponding to a pair of spots comprising a sub-wavelength defect in a locally isotropic section of substrate **60** represents information about the sub-wavelength defect relative to a reference sub-wavelength defect. The reference sub-wavelength defect has properties of the locally isotropic section and dimensions similar to those of the defect. Accordingly, properties measured include information about dimensions and location of the sub-wavelength defect in or on substrate **60**.

The accuracy of the interferometric compensation of background fields is high in the first and second embodiments for several reasons. The high accuracy of interferometric compensation is not dependent on the properties of pinholes in pinhole array beam-splitter **112**, *e.g.*, the diameter of a pinhole could change by a factor of 2 for example and/or the shape of a pinhole could change from a round aperture to a square aperture and the level of interferometric compensation for associated background fields would not change. The amplitudes and phases of background fields associated with a first spot of a pair of spots are the same as the amplitudes and phases of background fields associated with a second spot of a pair of spots independent of properties of pinholes in pinhole array beam-splitter **112**.

The throughputs of the first embodiment can be further increased by the use of a pinhole array beam-splitter that is coupled to input beam **24** by a guided-wave structure such as described in commonly owned U.S. Provisional Patent Application No. 60/445,739 (ZI-39) entitled "Multiple-Source Arrays Fed By Guided Wave Structures And Resonant Structures For Confocal And Near-Field Confocal Microscopy" and U.S. Patent Application No. ______filed February 6, 2004 (ZI-39) and also entitled "Multiple-Source Arrays Fed By Guided Wave Structures And Resonant Structures For Confocal And Near-Field Confocal Microscopy" both of which are by Henry A. Hill. The contents of the cited U.S. Provisional Patent Application and the U.S. Patent Application are incorporated herein in their entirety by reference.

A second embodiment is configured to measure the optical thickness of thin films on the surface of a substrate. The second embodiment comprises the interferometric confocal imaging system of the first embodiment with a thin film on the surface of substrate **60**.

The phase of $V_3(h_1, z_{1,m})$, $\Phi(h_1)$, changes by 2π as h_1 changes from a negative value to a positive value. The rate of change of phase $\Phi(h_1)$ with respect to h_1 at $h_1 = 0$ is related to the optical thickness of the thin film. In particular, the rate of change of phase $\Phi(h_1)$ with respect to h_1 at $h_1 = 0$ decreases as the thickness of the thin film increases. Electronic processor and controller **80** analyzes the arrays of measured conjugated quadratures for the array of rates of change of phase $\Phi(h_1)$ with respect to h_1 at $h_1 = 0$ for information about the thickness profile of the thin film. A film may be detected and its thickness measured for a thickness greater than or of the order of 5 nm.

An important feature of the second embodiment is that the properties of the thin film may be obtained with a lateral spatial resolution substantially equal to a diffraction-limited resolution of an interferometric confocal imaging system operating with a high numerical aperture, *e.g.*, 0.9.

The second embodiment may also be configured to measure the properties of substrate **60** and/or the thin film by the use of different polarization states for reflected/scattered beams from the array of common spots on substrate **60**. A

polarization state for the reflected/scattered beams is selected by apodizing the pupil of interferometer system **110**. The apodization corresponds to dividing the pupil into 4 equal pie sections and blocking the transmission of two diametrically opposite pie sections. The apodization for example permits the restriction of the reflection/scattering to take place substantially as either s or p polarizations. The state of polarization for the reflected/scattered beams is changed by changing the polarization state of input beam **24** and/or rotating the apodizing pie sections about an optical axis of the imaging system.

The use of different states of polarization for reflected/scattered beams represents an important advantage.

The first and second embodiments may also be configured for quad-homodyne detection such as described herein and in cited U.S. Provisional Patent Application No. 60/442,858 (ZI-47) and cited U.S. Patent Application filed Jan. 27, 2004 (ZI-47) entitled "Apparatus and Method for Joint Measurements of Conjugated Quadratures of Fields of Reflected/Scattered Beams by an Object in Interferometry" (ZI-47).

A third embodiment is shown schematically in Fig. **3**. The third embodiment can be configured to be functionally equivalent to the first and second embodiments. The primary difference between the first and second embodiments and the third embodiment is replacement of the pinhole array beam-splitter **112** with traditional confocal pinhole arrays **112A**, **112B**, and **112C**.

Referring to Fig. **3**, input beam **24** is incident on polarizing beam-splitter **330** and a first portion thereof is transmitted as a measurement beam of interferometer **410** and a second portion thereof is reflected as a reference beam of interferometer **410** after reflection by mirrors **332** and **334**. The measurement beam and the reference beam are incident on pinhole arrays **112A** and **112B**, respectively. Pinhole arrays **112A** and **112B** are each conjugates of pinhole array **112C**.

A portion of the reference beam incident on pinhole array **112B** is transmitted by beam-splitter **340** and a portion thereof focused by lens **360** to an array of spots on pinhole array **112C**.

A portion of the measurement beam incident on pinhole array **112A** is transmitted by beam-splitter **340** and first and second portions thereof are focused to

arrays of spots on substrate **60**. The first portion is focused to a first array of spots after a reflection and transmission by polarizing beam-splitter **342**, a double pass through quarter-wave plate **346**, reflected by concave mirror **350**, and focused by lens **354**. The second portion is focused to a second array of spots after a transmission and reflection by polarizing beam-splitter **342**, a double pass through quarter-wave plate **348**, reflected by convex mirror **352**, and focused by lens **354**. The description the first and second arrays of spots is the same as description of the corresponding arrays of spots of the first and second embodiments. The relative transverse and longitudinal shifting the first and second arrays of spots is controlled by rotations and longitudinal displacements of concave mirror **350** relative to convex mirror **352**. The orientation of optical system **310** which in practice is at an angle of 45 degrees to the plane of Fig. **3** is however shown as oriented in the plane in Fig. **3** in order to simplify the description without limiting the scope or spirit of the present invention.

Portions of the measurement beams that form the first and second arrays of spots are reflected/scattered by substrate **60** as first and second arrays of return measurement beam components, respectively. The first array of return measurement beam components retraces the path of its progenitor array of measurement beam components through imaging system **310** and a portion thereof is focused to an array of spots at pinhole array **112C** after reflection by beam-splitter **340**. The second array of return measurement beam components retraces the path of its progenitor array of measurement beam components through imaging system **310** and a portion thereof is focused to an array of spots at pinhole array **112C** after reflection by beam-splitter **340**.

The description of the two arrays of spots at pinhole array **112C** is the same as portion of the description given for the corresponding arrays of spots in the first and second embodiments at pinhole array beam-splitter **112** except that the displacements of the spots are not reduced by the factor $1/n$. The index of refraction of the medium contiguous to pinhole array **112C** is assumed to be 1 although it could be otherwise without departing from the scope and the spirit of the present invention.

Portions of the superimposed array of spots and of the reference beam are transmitted by pinhole array **112C** and detected by detector **70** after transmission by analyzer **362** to generate electrical interference signal **72**. Analyzer **362** mixes the polarization states of the transmitted portions of the superimposed array of spots and of the reference beam.

The description of input beam **24** is the same as corresponding portions of the description given for input beam **24** of Fig. **1a** with beam-conditioner **22** configured as a two-frequency generator and phase-shifter shown in Fig. **1b** and beam **20** comprising a single frequency component. Input beam **24** comprises two components that have different frequencies and each component has two components of different states of plane polarization. The relative phases of the components of input beam **24** are shifted between different values according to control signal **74** generated by electronic processor and controller **80** as described in the discussion of beam-conditioner **22**.

The remaining portion of the description of the third embodiment is the same as corresponding portions given for the first and second embodiments.

In some embodiments, pinhole array beam-splitter **112** may be scanned in a direction opposite to the direction of scan of substrate **60** and with a speed such that the conjugate images of the pinholes of pinhole array beam-splitter **12** stay superimposed with spots on or in substrate **60** that are being imaged. This scanning mode of operation is analogous to the relative motions of reticle stage and a wafer stage of a lithography tool operating in a scanning mode. The issue of traditional critical alignment of conjugate confocal pinholes in a confocal microscopy system is nonexsistent, *i.e.* the registration of the pinholes generating the array of reference beams and the pinholes generating the array of measurement beams is automatic.

In certain end use applications, the interior of substrate **60** is imaged. In this case, there will be aberrations introduced. In another embodiment, compensation for aberrations is accomplished by introducing a thin layer (the thin layer has an index of refraction different from lens **150**) between lens **150** and pinhole array beam-splitter **112** such as described in commonly owned U.S. Provisional

Application No.. 60/444,707(ZI-44) entitled "Compensation of Effects of Mismatch in Indices of Refraction At a Substrate-Medium Interface in Confocal and Interferometric Confocal Microscopy" and U.S. Patent Application No. ______filed February 4, 2004 (ZI-44) and also entitled "Compensation for Effects of Mismatch in Indices of Refraction at a Substrate-Medium Interface in Confocal and Interferometric Confocal Microscopy" both of which are by Henry A. Hill. The contents of the U.S. Provisional Patent Application and the U.S. Patent Application are incorporated herein in there entirety by reference.

A fourth embodiment comprises the interferometer system of Figs. **1a**-**1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 5,760,901. In the fourth embodiment, beam-conditioner **22** is configured as the two frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 5,760,901 are configured to operate in either the reflection or transmission mode. The fourth embodiment has reduced effects of background because of background reduction features of cited U.S. Patent No. 5,760,901.

A fifth embodiment comprises the interferometer system of Figs. **1a**-**1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 5,760,901 wherein the phase masks are removed. In the fifth embodiment, beam-conditioner **22** is configured as the two frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 5,760,901 are configured to operate in either the reflection or transmission mode. The fifth embodiment with the phase masks of embodiments of cited U.S. Patent No. 5,760,901 removed represent applications of confocal techniques in a basic form.

A sixth embodiment comprises the interferometer system of Figs. **1a**-**1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 6,480,285 B1. In the sixth embodiment, beam-conditioner **22** is configured as the two-frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 6,480,285 B1 are

configured to operate in either the reflection or transmission mode. The sixth embodiment has reduced effects of background because of background reduction features of cited U.S. Patent No. 6,480,285 B1.

A seventh embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 6,480,285 B1 wherein the phase masks are removed. In the fifth embodiment, beam-conditioner **22** is configured as the two-frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 6,480,285 B1 are configured to operate in either the reflection or transmission mode. The seventh embodiment with the phase masks of embodiments of cited U.S. Patent No. 6,480,285 B1 removed represent applications of confocal techniques in a basic form.

An eighth embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** comprising an interferometric near-field confocal microscope such as described in cited U.S. Patent No. 6,445,453 (ZI-14). In the eighth embodiment, beam-conditioner **22** is configured as the two-frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 6,445,453 are configured to operate in either the reflection or transmission mode. The eighth embodiment of cited U.S. Patent No. 6,445,453 in particular is configured to operate in the transmission mode with the measurement beam separated from the reference beam and incident on the substrate being imaged by a non-confocal imaging system, *i.e.*, the measurement beam at the substrate is not an image of an array of pinholes but an extended spot. Accordingly, the corresponding embodiments of the eighth embodiment represent an application of bi-homodyne detection method in a non-confocal configuration for the measurement beam.

Other embodiments may use the quad-homodyne detection method instead of the bi-homodyne detection method as variants of the embodiments. For the embodiments that are based on the apparatus shown in Figs. **1a-1c**, the corresponding variants of the embodiments that use the quad-homodyne detection method use variants of the apparatus shown in Figs. **1a-1c**. In the variants of the

apparatus such as used in the first embodiment, microscope **220** is modified to include a dispersive element such as a direct vision prism and/or a dichroic beam-splitter. When configured with a dichroic beam-splitter, a second detector is further added to the system. Descriptions of the variants of the apparatus are the same as corresponding portions of descriptions given for corresponding systems in cited U.S. Provisional Application No. 60/442,982 (ZI45) and U.S. Patent Application No. _______filed January 27, 2004 (ZI-45) entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter".

Variants of embodiments may be configured to use the double-homodyne detection method for generation of non-joint measurements of conjugated quadratures. Input beam **24** of the variants of the embodiments comprise four frequency components and with the design of the dispersion of a direct vision prism and/or a dichroic beam-splitter such as described with respect to embodiments that are configured to use the quad-homodyne detection method and the selection of the four frequencies such that each of the four frequency components of beam **32** are directed to different pixels of detector **70**. Four arrays of electrical interference signal values are obtained simultaneously and processed for amplitudes of conjugated quadratures using the procedure described herein for the single-homodyne detection method.